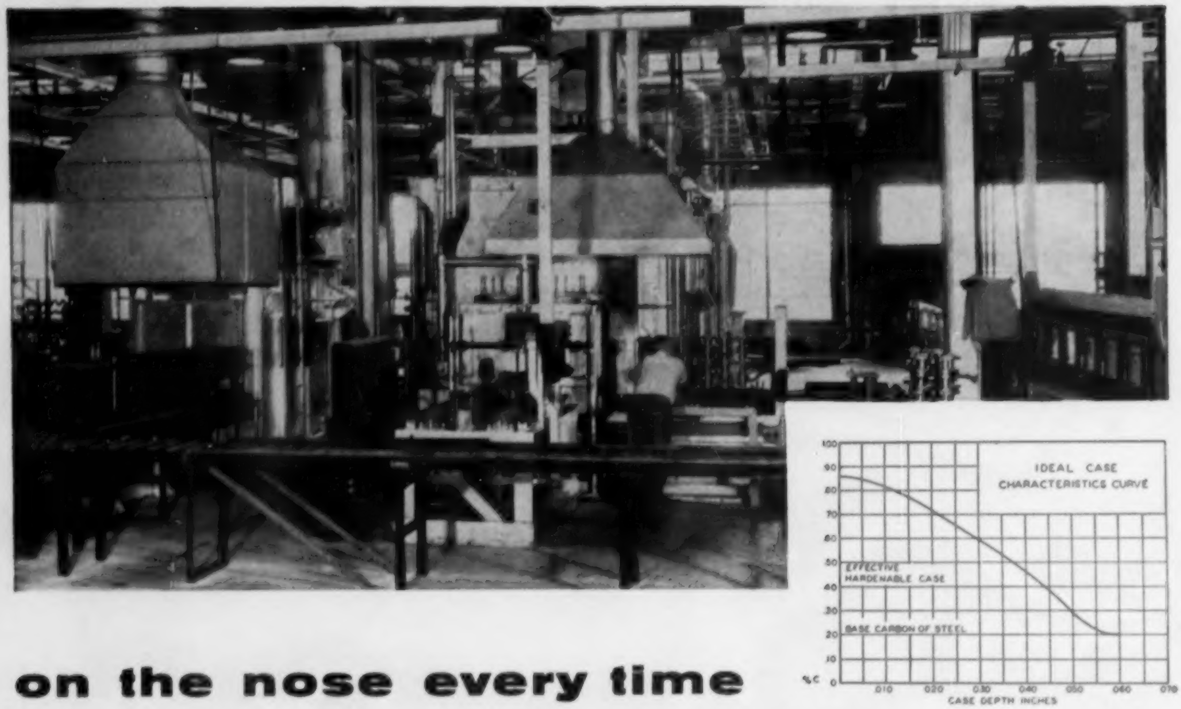
METAL PROGRESS

AUGUST 15, 1955

REPORTS OF 19 TECHNICAL COMMITTEES
OF THE AMERICAN SOCIETY FOR METALS


IDEAL CASE CHARACTERISTICS CURVE
EFFECTIVE HARDENABLE CASE
BASE CARBON OF STEEL
%C
0
10
20
30
40
50
60
70
80
90
100
.010
.020
.030
.040
.050
.060
.070
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Write for Literature H-54-2.

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Metal Progress

Volume 68, No. 2-A

August 15, 1955

Two issues of Metal Progress are being sent to all ASMembers and subscribers in August. The one dated August 1, 1955, has the usual editorial direction. This one dated August 15, 1955, is confined to reports of 19 ASM technical committees and it can be used along with the July 15, 1954, reports to supplement the ASM Metals Handbook.

Prepared under the direction of the

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Published monthly except bi-weekly in August, by AMERICAN SOCIETY FOR METALS. Publication office, Mt. Morris, Ill. Editorial, executive and advertising offices, 7301 Euclid Ave., Cleveland 3, Ohio. Subscription $7.50 a year in U.S. and Canada; foreign $10.50. Single copies $1.50; special issues $3.00. . . . The AMERICAN SOCIETY FOR METALS is not responsible for statements or opinions printed in this publication . . . Requests for change in address should include old address of the subscriber; missing numbers due to "change of address" cannot be replaced. Claims for non-delivery must be made within 60 days of date of issue. No claims allowed for overseas subscribers. Entered as second-class matter at the Post Office in Mt. Morris, Ill.

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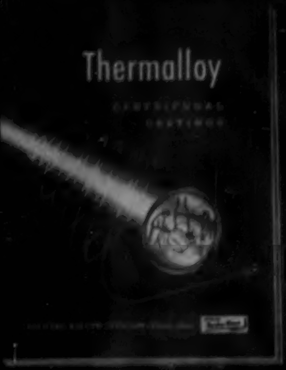
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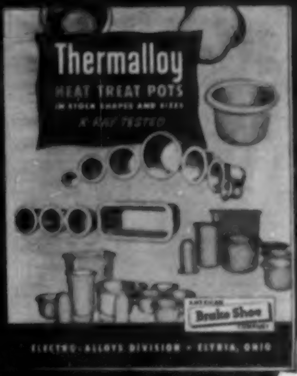
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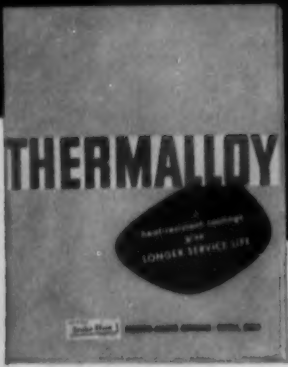
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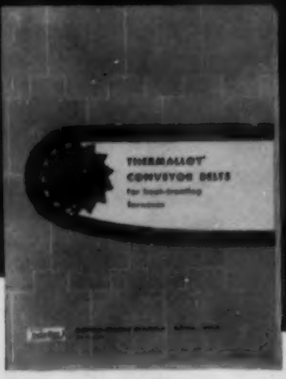
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Conveyor Belt
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Metal Progress

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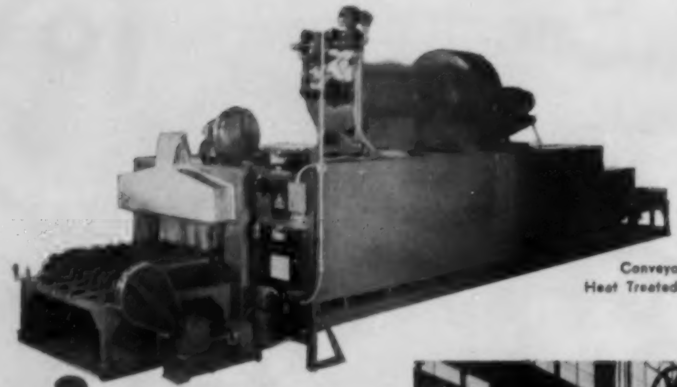

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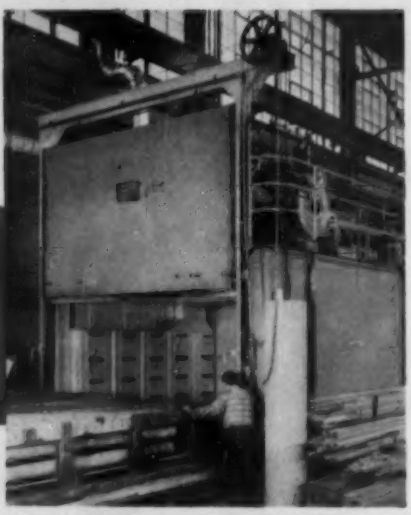

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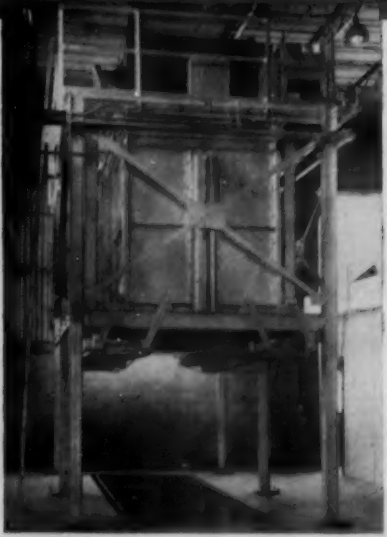

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As I was saying...

I WAS STARTLED out of my hide almost when they yelled that I needed to write another column this month to fill the space reserved for me in the 13th issue of *Metal Progress*, which is, as you know, devoted entirely to supplemental material for the Metals Handbook. But I was rather glad at that, because it gave me an opportunity to express some thoughts about some activities I have observed going on around headquarters for the past year. First, there was the getting-together of a list of subject material by the Metals Handbook Committee and Dr. Lyman, the editor; and then the making up of a list of members to be invited to serve on each committee. The chairman of each committee was the No. 1 man approached, and, with the chairman set, the make-up of the committee progressed smoothly. The committees were assigned by Editor Lyman to his two assistants – mechanical subjects to Carl Gerlach and metallurgical subjects to James Hontas – and then the fur flew. The committees were scheduled for meetings, either at A.S.M. Headquarters or at some more convenient city, where plans were outlined and jobs assigned to the members of the task force.

You all are aware how good committees work and the Handbook groups were all par excellence. Soon there were manuscripts for review and transmittal to members for their consideration and then the final draft of the article. With approval of the articles, the committees' work was "at ease", but now the beehive of activity got going in Cleveland in preparation of the articles for publication. There were extra draftsmen to hire (and supervise), cuts to be made, type to be set, proof to be read, pages made up for the pressroom and a thousand and two others things that had to be done.

It was then that I observed the burning of the midnight kw. with Taylor and Carl and John Parina (who was appointed associate editor of the Handbook to replace James Hontas, who became *Metal Progress* advertising representative in the New York and Philadelphia territory) enjoying the cool of the evening in their offices. But where there was a will there was a way and this second Supplement to the Handbook has now been placed in your hands.

It is a monumental piece of work, the collecting and reducing to plain understandable language of the final word in metalworking practice and placing the results in printed form for all to read and use.

So, to these faithful and conscientious members of the Handbook Committees, the reviewers, the staff, and their assistants, and all who in any way contributed to this splendid supplement, will go the thanks and appreciation of the entire A.S.M. membership for a job well done. As secretary for the twenty-five thousand members, I am authorized to say: We thank you, one and all!

Cordially yours,

Bill

W. H. EISENMAN, *Secretary*
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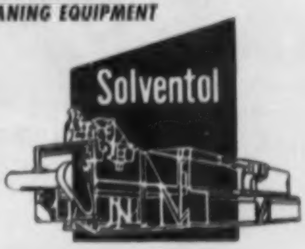

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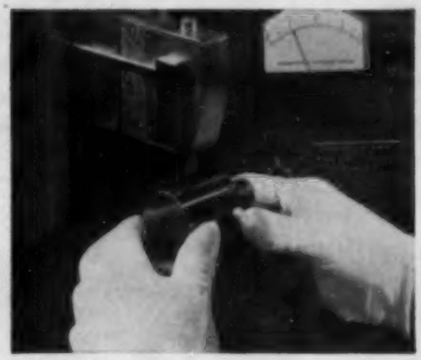
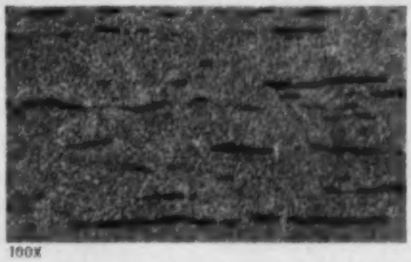


Graph-Mo steel master plug gage (above) used in 12-year stability test. Photomicrograph (below) shows free graphite and diamond-hard carbides that give Graph-Mo unusual wear resistance.



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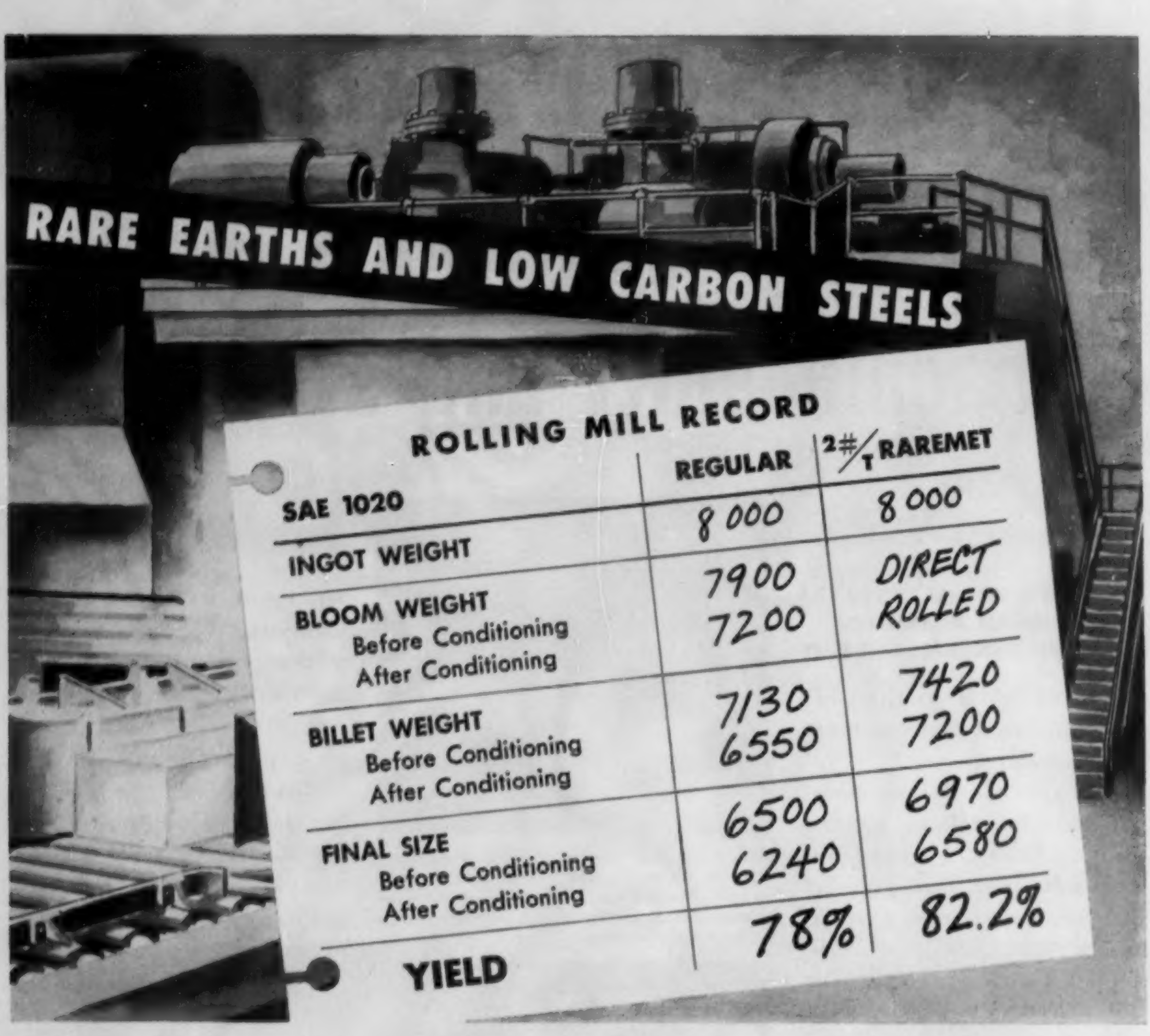

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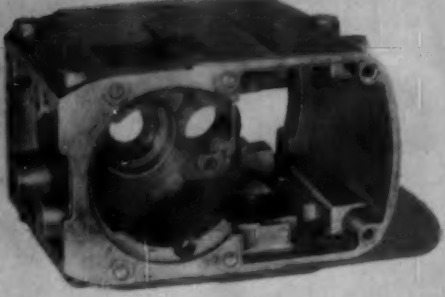

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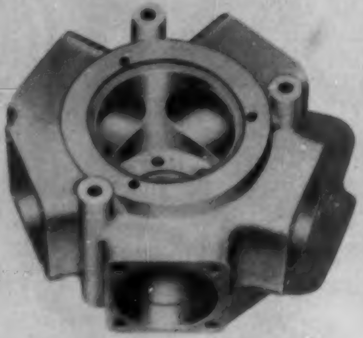

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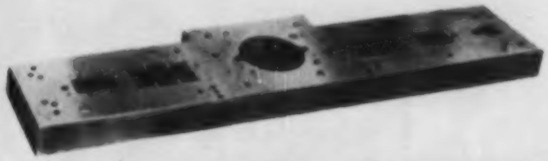

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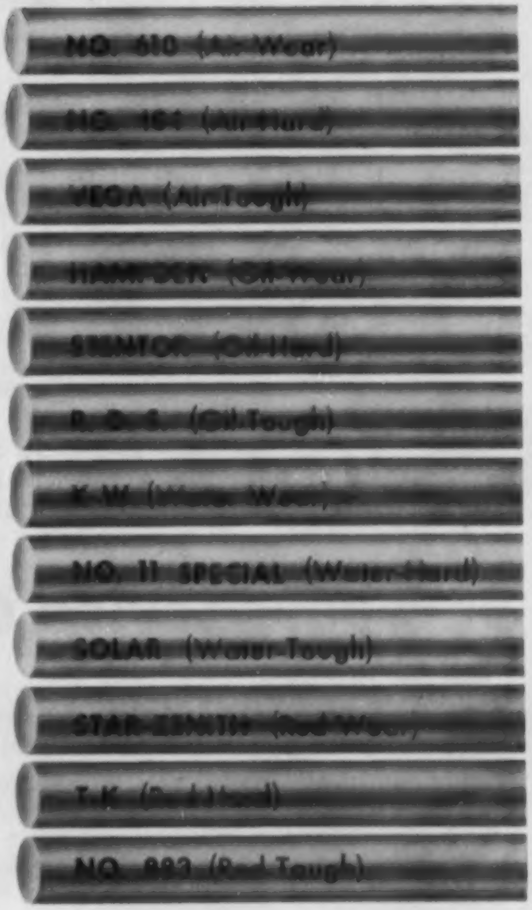

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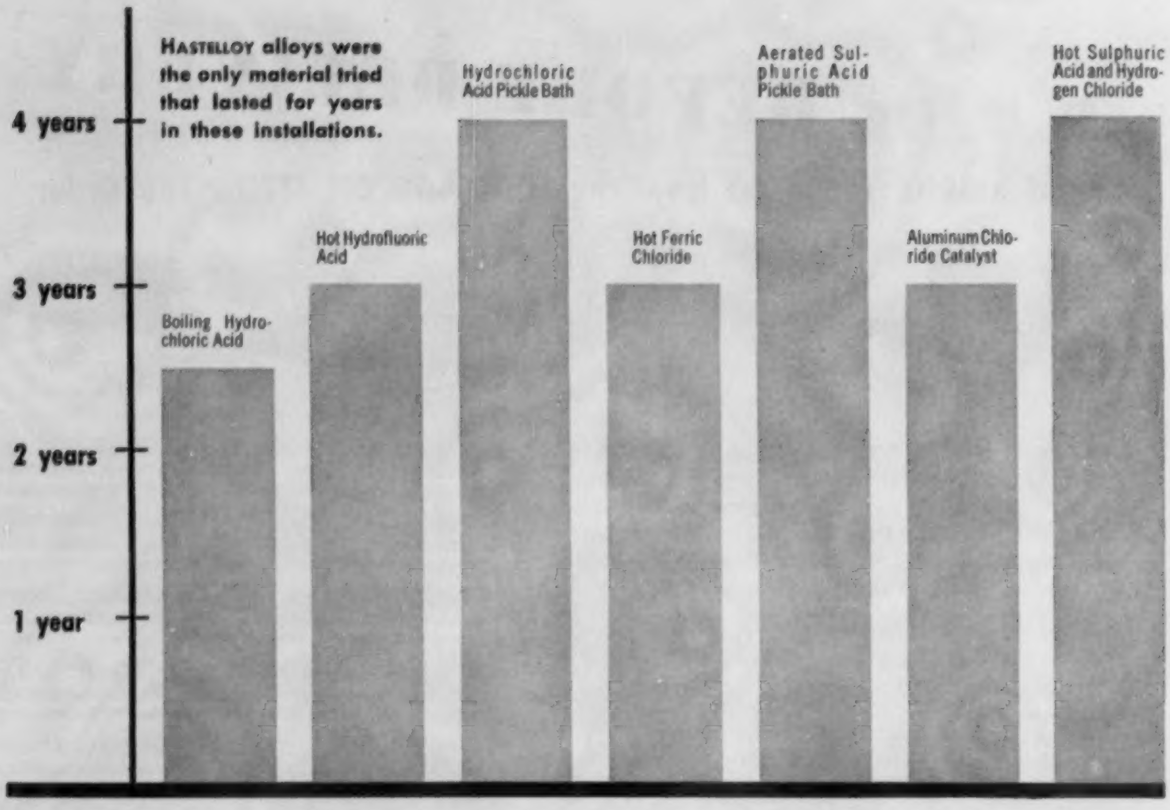

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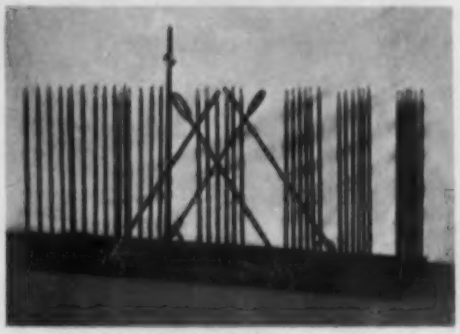

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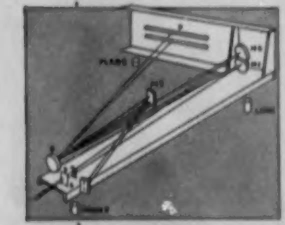

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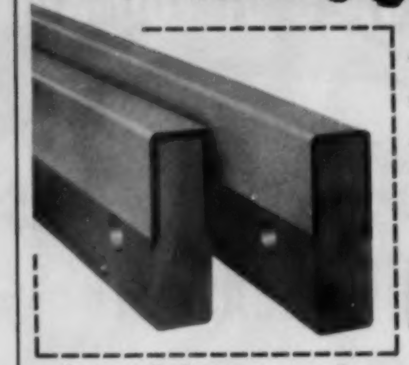

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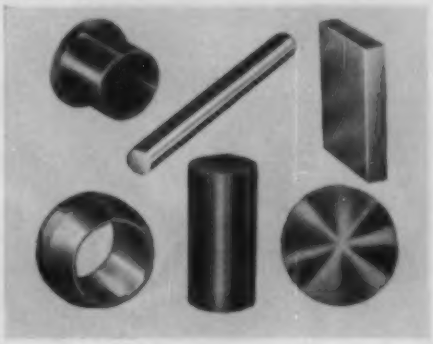

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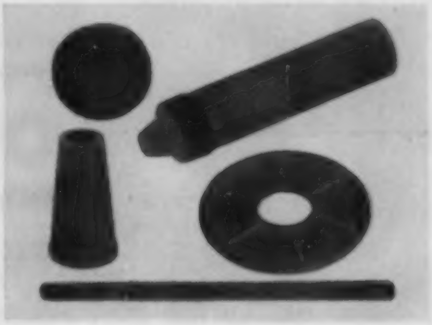

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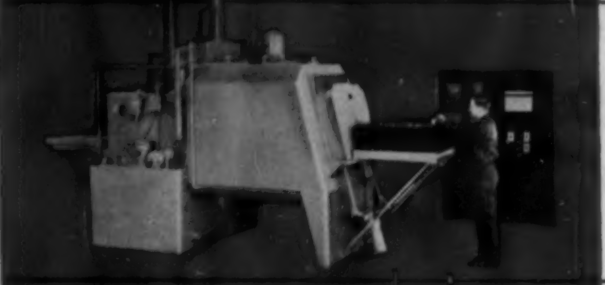

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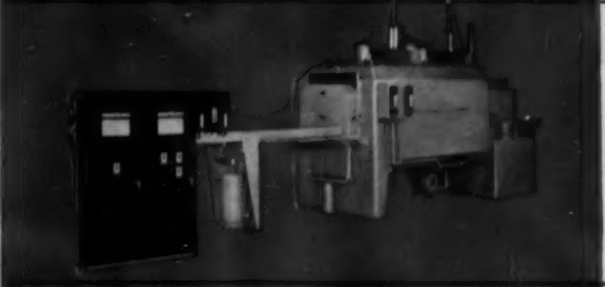

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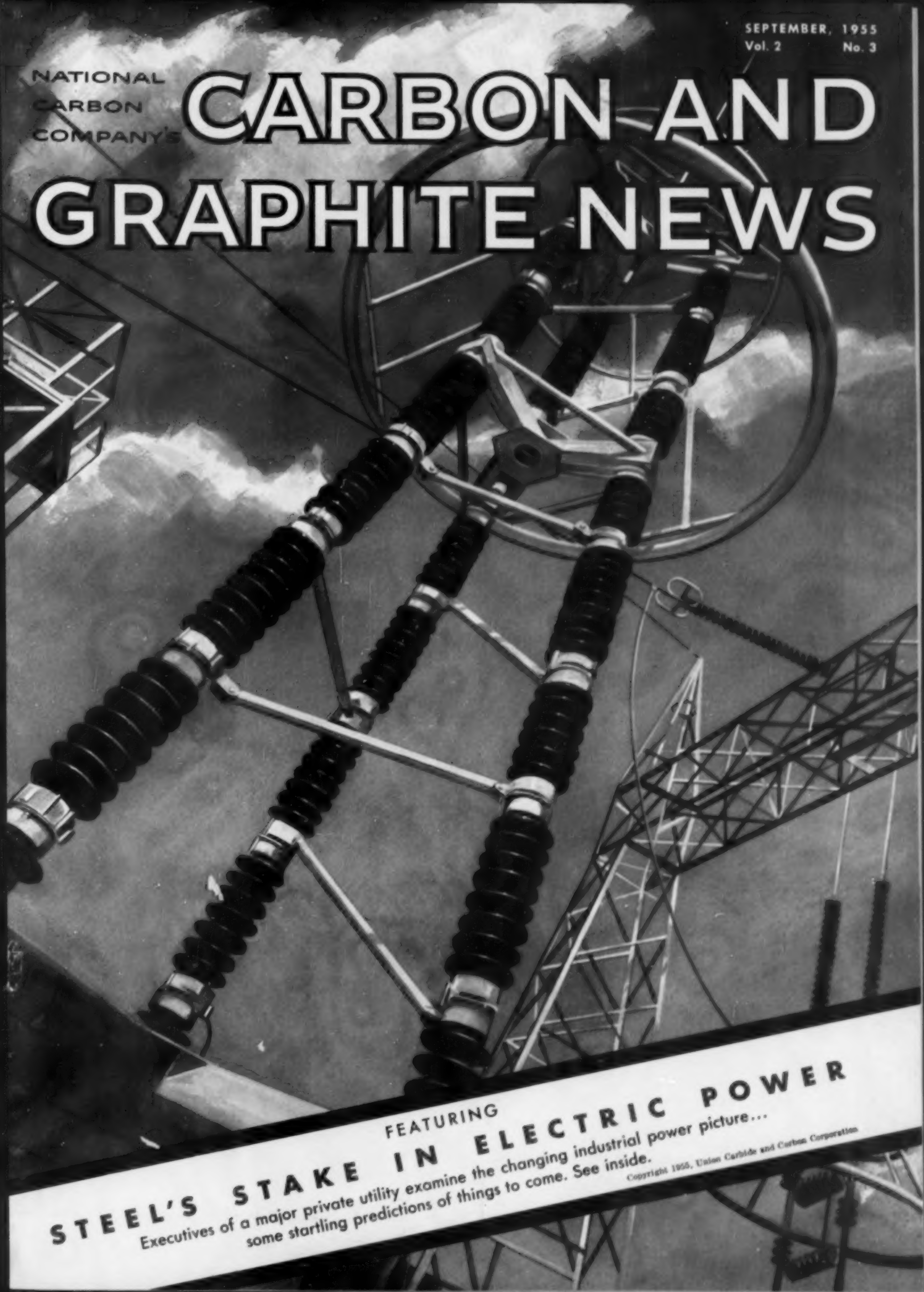

FEATURING

STEEL'S STAKE IN ELECTRIC POWER

Executives of a major private utility examine the changing industrial power picture... some startling predictions of things to come. See inside.

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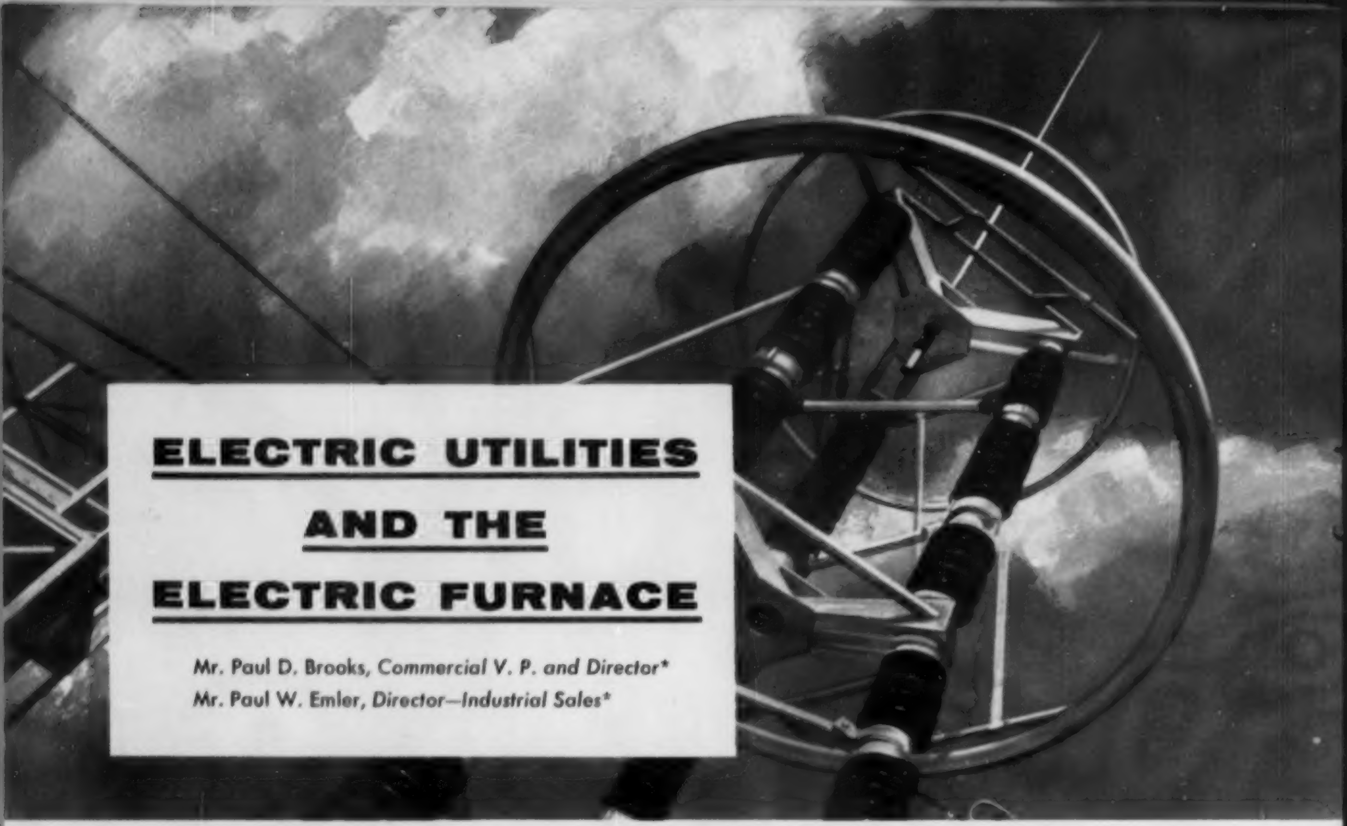


ELECTRIC UTILITIES AND THE ELECTRIC FURNACE

*Mr. Paul D. Brooks, Commercial V. P. and Director**
*Mr. Paul W. Emler, Director—Industrial Sales**

BEGINNINGS AND DEVELOPMENT OF ELECTRIC FURNACE USE

The use of the electric arc for metal melting extends back to the very beginning of the electrical era. It was recognized very early that the electric arc is a means of obtaining elevated temperatures and higher degrees of heat concentration than is possible through the combustion of fuels. Later, Sir William Siemens, using a dynamo of about 4 hp. capacity, applied the electric arc principle in melting platinum, iridium, steel and iron.

It was not until the end of the 19th century that any serious effort was made to use this melting process industrially. One reason for this unproductive interval was the absence of dependable electric power generating facilities great enough to meet demands for tonnage melting. In 1899, Dr. Paul Heroult began his extensive work on the production of steel from pig iron and later from common scrap iron. He also attacked the problem of refining steel and found that the electric furnace possessed features that permitted refining operations to be carried far beyond anything possible in the open-hearth furnace. The direct arc furnace, as we know it today, is a composite of the original Heroult furnace to which have been added numerous features, developed by other investigators, that time and experience have proved to be essential to the satisfactory and economical operation of the furnace.

The first electric arc melting furnace used in this country was installed in Syracuse in 1906. The original furnace was a 6 ton, 3 phase unit of 800 kw. capacity.

The crucible process for the production of special steels was gradually replaced by the electric arc melting process and, by 1918, 282 such furnaces, having an annual production capacity of 500,000 tons, were in operation. From that time until 1940, growth was moderate, capacity reaching 1.7 million tons. Beginning in 1940, electric furnace capacity increased at a rapid rate, reaching 4.6 million tons in 1943. Much of this expansion was due to the heavy demand for high-grade alloy steel and castings for the war effort.

With the end of the war, a large idle capacity of electric furnaces developed as production of electric steel dropped to 2.6 million tons. This availability of idle furnace equipment was one factor which induced experimentation in the use of the electric process for the production of plain carbon steel. It was found that, under a given set of conditions, the overall costs in electric furnace production of plain carbon steel might be as low as, or lower than, the overall costs of the open-hearth process. Older ideas about manufacturing costs of electric steel had to be revised, due to improved furnace design, larger transformer capacities, new process techniques and the fact that electric power cost had remained practically constant while the costs of most other commodities had increased. This experimentation led to an expansion of elec-

*American Gas and Electric Service Corporation tric furnace capacity and to an increase in electric steel production from a post-war low of 2.6 million tons in 1946 to an all-time high of 7.3 million tons in 1953 (see Figure 1.)

One result of post-war interest in the electric arc furnace as a producer of low carbon steel was the study, "Comparative Economics of Open-Hearth and Electric Furnaces for Production of Low-Carbon Steel", prepared by Battelle Memorial Institute and sponsored by the Electric Furnace Survey Group. This group was comprised of a number of Electric Utility Companies, including an affiliated company of American Gas & Electric and Bituminous Coal Research, Inc. The study, which was based on plants having annual capacities of 250,000, 500,000 and 1,000,000 tons, concluded that for cold-charge practice, the electric furnace shop will have a lower overall production cost than the open-hearth shop and, for hot-metal charge, there will be little difference in overall operating costs between the two.

Operational advantages of the electric arc furnace have been well established and are recognized by all steel manufacturers. They include closer temperature control, closer metallurgical control, high heat efficiency, lower installation cost per unit of production, flexibility in operation to meet changing production schedules and flexibility in type of product.

The arc furnace, in addition to its place in ingot steel production, accounts for practically all the steel castings that are made in this country and it is rapidly gaining acceptance in the iron foundry. It is widely used with the cupola to duplex cupola iron and, by this operation, not only improves the quality of the iron but reduces the cost as well.

ELECTRIC POWER FOR ARC FURNACE OPERATION

Three important factors to be considered when selecting equipment to increase steel-making capacity are: the availability of an adequate electric power supply; the present cost of power; and what the relation between electric power cost and the cost of fuel for open-hearths is likely to be during the twenty or twenty-five year life of the equipment. Just as a lack of sufficient electric facilities delayed application of the arc furnace to industry in the 19th century, so now the availability of dependable electric capacity at reasonable and stable cost has hastened the recent growth of electric furnace capacity.

The remainder of this paper will discuss questions of electric power supply and power cost for electric arc furnaces. The discussion will generally represent the experience of the electric utility industry, but it will be based in part on our own American Gas & Electric experience and planning.

Electric arc furnace load is no stranger to the AGE System. Our experience in supplying this demand covers a span of more than thirty-five years. After serving a number of smaller furnaces, the first 100 ton arc furnace ever built was connected to our system at Canton, Ohio, in 1927. Since that time, electric arc furnace capacity served by the AGE System has grown to more than one-half million kva. In all cases, we have been able to work out in advance economical means to satisfactorily serve proposed arc furnace installations. We certainly feel that this type of load is a desirable one and, based on our past experience, look forward to serving many more arc furnace installations.

Before looking ahead at what future electric utility system capacities and electric power cost may be, let us look first at past electric load growth and power cost. Figure 2 shows the peak loads that have occurred on electric utility systems since 1930. Figure 3 shows the cost trend of electric power delivered to industry. It is apparent that during the time that electric demand quadrupled the unit cost of power delivered to industry was reduced 30%. Even during the years between 1940 and 1952, when commodity prices doubled, electric power costs remained stable, as shown by Figure 4.

The reasons for past reductions in power cost are important because the same factors will affect *future* costs. First, the electric industry is a dynamic industry. Reduction in cost of service naturally leads to expansion in use of service; and expansion in use of service makes possible still further reduction in power cost. Expansion in use of service is also affected by population growth, higher standards of living, the shorter work week and changing industrial technology. Table 1, which shows the relation of Employment, Productivity and the use of Electricity in Manufacturing Industries since 1920, clearly indicates one reason for this increase in electric power. Between 1920 and 1953, while the amount of labor per unit of production, expressed as million man-hours per FRB unit, was decreasing from 539 to 210, electric energy used per unit of production increased from 655 to 1,460 million kw-hr. At the same time, power used by industry increased from 1.21 to 6.94 kw-hr. per man-hour.

The two principal elements in the cost of electric power are the cost of generating the power and the cost of transmitting it to the user. Many technological improvements in generation and transmission have contributed to the axiom that the cost of power decreases as the demand for power grows. Among these advances are:

(Continued on next page)

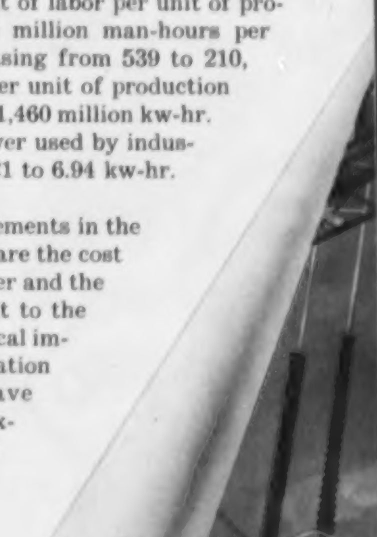
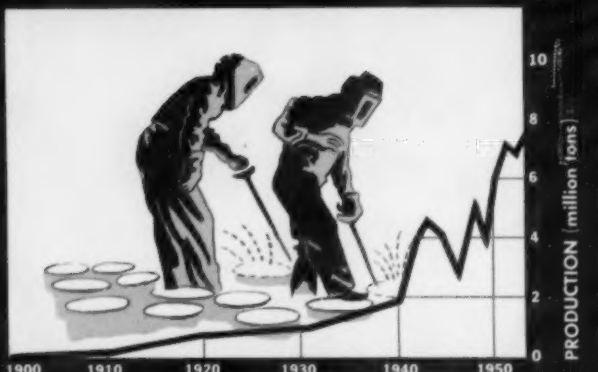


Table 1. Employment, Productivity and Use of Electricity in Manufacturing Industries

YEAR	FRB INDEX OF MFRS.	MILLION kw-hr. PER FRB INDEX	MILLION MAN-HRS. PER FRB INDEX	kw-hr. PER MAN HOUR
1920	39	655	539	1.21
'25	48	798	383	2.08
'30	48	1076	336	3.21
'35	46	1206	301	4.01
1940	66	1197	259	4.62
'45	110	1107	259	4.28
'50	113	1454	224	6.48
'53	136	1460	210	6.94

Source: Federal Reserve Bulletin · Handbook of Labor Statistics
Monthly Labor Review · Historical Statistics of the U. S.
Federal Power Commission · U. S. Census of Manufacturers

Figure 1. Annual Production of Electric Furnace Steel in the United States



Source: American Iron and Steel Institute

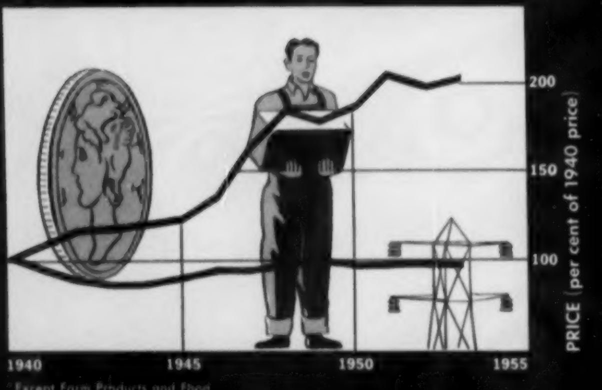
adoption of the reheat cycle, higher steam temperatures and pressures, single reheat boiler-turbine units, centralized generating-plant controls, simplified power-plant design and layout, and larger-sized generating units. A direct result of these improvements was the increase in generating-plant fuel-efficiency as shown by Figure 5.

This relation between electric load growth and power cost is one of the principal keys to future power costs. Let us look now at the peak loads which are expected for future years, shown by Figure 6. The 1975 load on electric utility systems is expected to be between triple and quadruple the 1953 load. We do not know precisely what new loads and increases in existing loads will occur to bring about this large increase in power requirements. We can foresee, however, and are planning for, tremendous advances requiring very large amounts of power in the steel and metal industries, the chemical industry, in electric space heating and air conditioning and other uses. These uses, combined with the effects of population growth and improved living standards, are expected to bring the peak loads indicated.

Assuming a stable economy and the load increases predicted, cost of electric power is likely to continue to decline. The major portion of electric power generated in this country is from steam generation using coal as a fuel, and this situation is likely to continue for another twenty years. Future coal prices are, therefore, important in estimating future power costs, just as future prices of gas and oil are important factors in open-hearth furnace costs. Although variables, such as technological changes, governmental controls and basic supplies, make predictions difficult, the Battelle study did devote considerable attention to the subject. Figure 7 is from that study and indicates that, while coal prices are likely to remain stable or decrease in the future, oil and gas prices will probably increase. Many other factors will contribute to the probable decline in power costs, but two developments pioneered by AGE are indicative of what will be accomplished:

The first of these is the development of Super-Critical Pressure steam generation. The 4,500 psi, 1,150 Degree F, double-reheat-steam, power generating unit, which is now under construction at

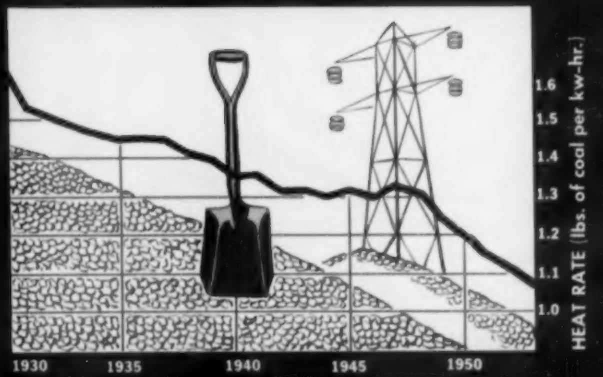
Figure 4. Price of Electric Power sold to Industry compared to Price of all other Commodities*



*Except Farm Products and Food

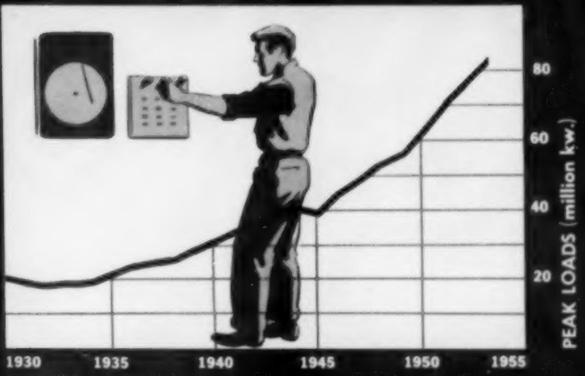
Source: Edison Electric Institute, Bureau of Labor Statistics

Figure 5. Average Fuel Burning Efficiency of all Utility Steam Plants



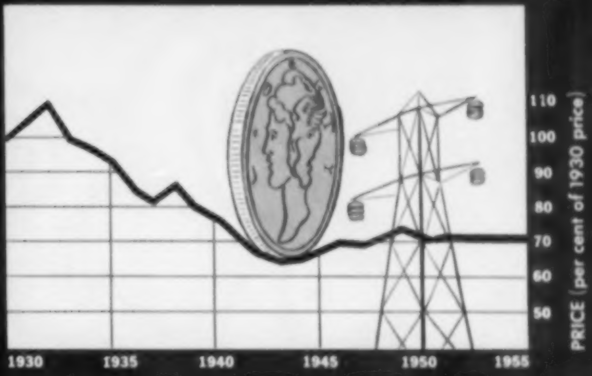
Source: Federal Power Commission

Figure 2. Peak Loads—Total Electric Utility Industry



Source: Edison Electric Institute

Figure 3. Price of Electric Power sold to Industrial Customers—Total Electric Utility Industry



Source: Edison Electric Institute

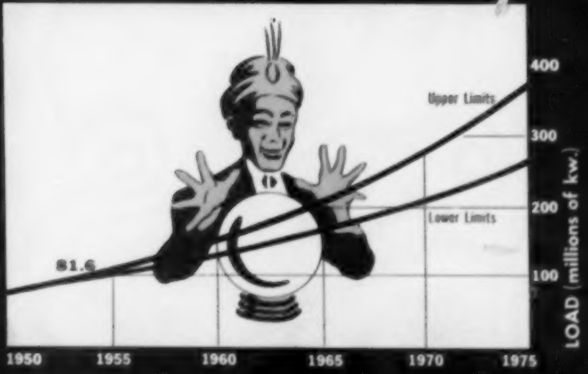
Philo, Ohio, will be the world's most efficient unit with an expected heat rate of 8,500 B.t.u. per kw-hr. The average of all steam plants operating in this country was 13,366 B.t.u. per kw-hr. in 1952. The large increase in power requirements in the future will mean that almost all generating equipment will be modern by today's standards; and, even assuming no further progress beyond the Philo unit, fuel used per kw-hr. in 1975 will be only about two-thirds of what it is now.

A second development pioneered by AGE is the use of 330-kv. transmission lines to handle today's loads and those of the future. One 330-kv. circuit will transmit about six times as much power as one 132-kv. circuit at a cost of only about twice that of the 132-kv. circuit. As loads grow, making higher voltage transmission practical, transmission costs per unit of power will decrease.

In addition to the above factors, which will tend to decrease power cost, there is Atomic Power. Undoubtedly, it will have its place in future power generation; but it is unlikely that anyone knows whether the time in which Atomic Power can be brought to fruition as a large-scale economic operation is of the order of five years or whether a much longer period will be required. We are now actively engaged in the research and development stage of the art of Atomic Power generation.

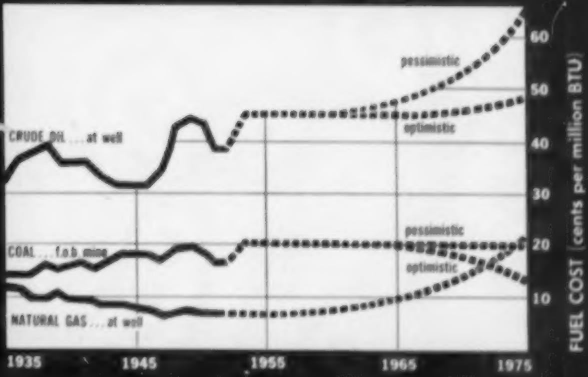
Based on all known factors, AGE is confident that power loads and power systems will grow tremendously in the future and that power costs are likely to continue decreasing. Electric power, which is industry's biggest bargain today, will be in an even better competitive position with the fuels of tomorrow. There will be adequate electric capacity to supply all of the needs of the country, including not only electric arc furnaces for the steel, metal and ferro-alloy industries but electric arc furnaces for calcium carbide plants, phosphorous plants and many others. The growth in electric system capacity will tend to solve many of the electric arc furnace supply problems which have been present in the past. Low cost electric power of adequate capacity, combined with the inherent advantages of the electric arc furnace and the improvements being made in furnace equipment and techniques, will all contribute to a continuing expansion of electric arc furnace applications.

Figure 6. Future Load Forecast—Total Electric Utility Industry



Source: Electric Power Survey Committee, Edison Electric Institute

Figure 7. Past, Present and Potential Trends in U.S. Price Levels of Primary Mineral Fuels



Source: Electric Furnace Survey Group Study, "Comparative Economics of Open-Hearth and Electric Furnaces for Production of Low-carbon Steel."

NATIONAL CARBON AS A CUPOLA REFRACTORY

TRADE-MARK

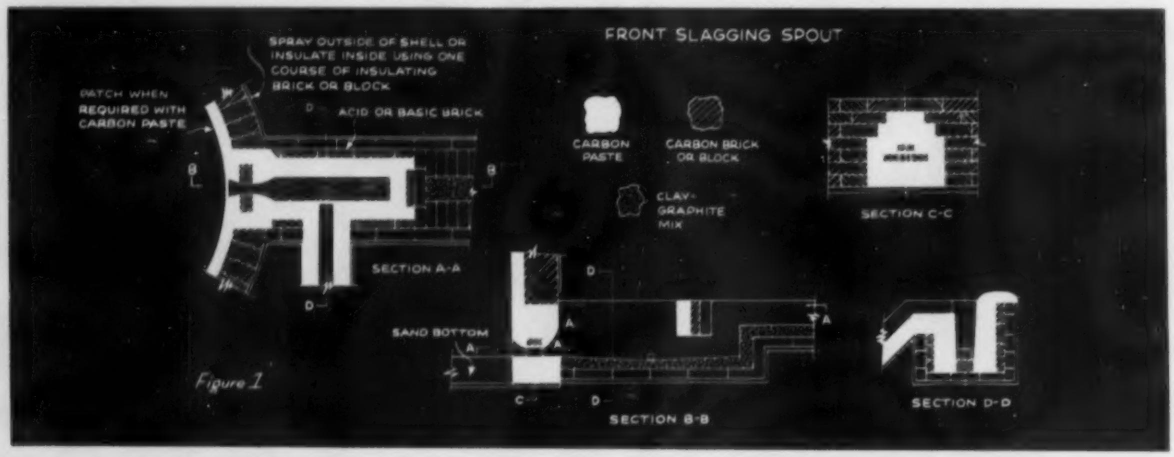


Figure 1

"The foundry industry today is in a period of transition. There are about 5,000 cupolas in the U.S. producing grey cast iron . . . and it's possible that no two foundries have precisely the same conditions or requirements. So don't expect a revolution overnight . . ."

This quotation from a veteran in the grey iron foundry field illustrates two important aspects of that industry today. One is an awareness of tradition. The other, a susceptibility to change. Together they comprise a basic philosophy of "Make Haste Slowly"—a hard one to beat when making policy for a period of sound, competitive growth.

Among the most interesting of the new practices to receive industry-wide attention is the use of carbon — in the form of blocks, brick shapes and paste — as a cupola refractory. Undoubtedly, the trend toward carbon refractories in the grey iron industry received impetus from its success in hearths, side-walls and even up to the mantles of blast furnaces — nearly 40% of which are now lined with carbon in some form.

PROPERTIES OF CARBON AS A CUPOLA REFRACTORY

Carbon is:

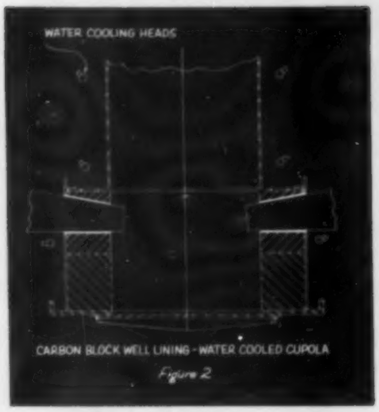
- Completely inert to the chemical effects of slag corrosion, either acid or basic
- Highly resistant to thermal shock and dimensionally stable
- Not wet by molten metals or slags
- High in abrasion resistance at elevated temperatures
- Low in absorption into the molten bath
- Available in all the forms in which other refractory materials are provided.

If these properties are considered in terms of the advantages each one offers the cupola operator, the value of carbon as a refractory is clearly evident. For example, its chemical inertness completely eliminates slag corrosion—undoubtedly the greatest single cause of damage to acid or basic linings. Breakage and joint failure due to shrinkage cease to be problems because of carbon's low coefficient of expansion. Clean-out of metal and slag is greatly accelerated by carbon's low adhesion to these materials. Since it has no melting point, carbon retains its favorable resistance to abrasion at all operating temperatures. Its low absorption into the bath rules out loss of refractory by this means. And, finally, because it is available in blocks, brick, shapes, paste and cement of various formulations, carbon requires no substantial change in conventional lining and maintenance practices.

APPLICATIONS

The merits of carbon for lining the front slagging trough or spout of the cupola are generally recognized. Troughs with carbon linings are giving economical, trouble-free service in both acid and basic cupolas. A typical trough lined with carbon brick and carbon ramming paste is illustrated in Figure 1. In carbon-lined troughs, such wear as occurs is due almost entirely to simple erosion and can readily be repaired with carbon paste which is baked in by the normal heat of operation.

In the cupola proper, carbon has found its most wide-spread use to date in the well zone. Carbon



well-linings have given very satisfactory service in both acid and basic cupolas, although the preponderance of installations so far is in the field of basic slag practice where the refractory first-cost differential is relatively small. Generally, it may be said that wherever it is desirable to operate a cupola, either acid or basic, for long periods, or where refractory costs are averaged out against large annual tonnages, carbon well-linings look good from any angle—including cost-per-ton of metal poured.

Figure 2 illustrates a type of cupola design wherein carbon lining of the well is virtually dictated by all considerations of economy and efficiency of operation. Here oxidation in the melt-zone is not a problem because external water cooling of the steel shell has eliminated refractories entirely from this area. The carbon-lined well may be expected to give from 6 months to 1½ years or more of service with only routine maintenance, and performance of the carbon refractory blocks is such that the bottom need be dropped only at very infrequent intervals.

This design, when it employs carbon in the well, offers a unique flexibility of operation in that slags may be varied from acid to basic to "neutral" as required to meet changing product specifications. This feature is especially interesting at a time when more and more foundries are being required to produce a greater variety of irons on short notice and under highly competitive conditions. Basic practice also substantially reduces sulphur content – an advantage which finds its chief application in low-sulphur base for the ultimate production of nodular or ductile iron.

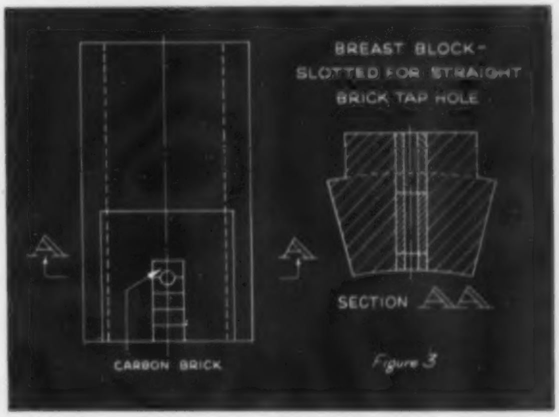
In addition to its use in trough and well, carbon has been very successful in breast and tap-hole construction. Several methods of application have been employed, with results indicating preference for a monolithic breast block of carbon, grooved to accommodate carbon and ceramic tap-hole brick (figure 3). The block is placed in the breast and the breast opening is closed with suitable ramming materials.

As regards melt-zone applications of carbon, experiments are now under way to develop a type of construction which will perform to economic advantage in this highly oxidizing atmosphere.

BLOCK, BRICK OR RAMMING PASTE?

Determination of the form in which carbon is used in the cupola should be made largely on the basis of economics.

For length of life, ease of maintenance and speed of installation, carbon block of the maximum size which can be handled by plant facilities are strongly recommended. Cost is about 2-2½ times that of carbon brick, but when averaged over the large tonnages of continuous or heavy, intermittent operation of the unit during the long life of the refractory, this consideration becomes negligible.



Carbon bricks, while physically the same material as the larger shapes, require longer to lay up and have a greater number of exposed joints. However, where production is intermittent, and carbon is being considered as a direct replacement for other types of refractory bricks, their lower first cost may determine their choice over block.

Carbon paste is used for maintenance of both pre-baked carbon brick and blocks and is handled much like any other plastic refractory patching material. Its cost – much lower than pre-baked carbon – has led to its use as a ramming-mix liner for the entire cupola well. While life is relatively short, such jobs compare favorably on all counts with refractory linings other than carbon. Frequently, carbon paste has supplanted other types of plastic patching materials with excellent results,

(Concluded on next page)

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even in wells and troughs lined with magnesite or fire clay brick.

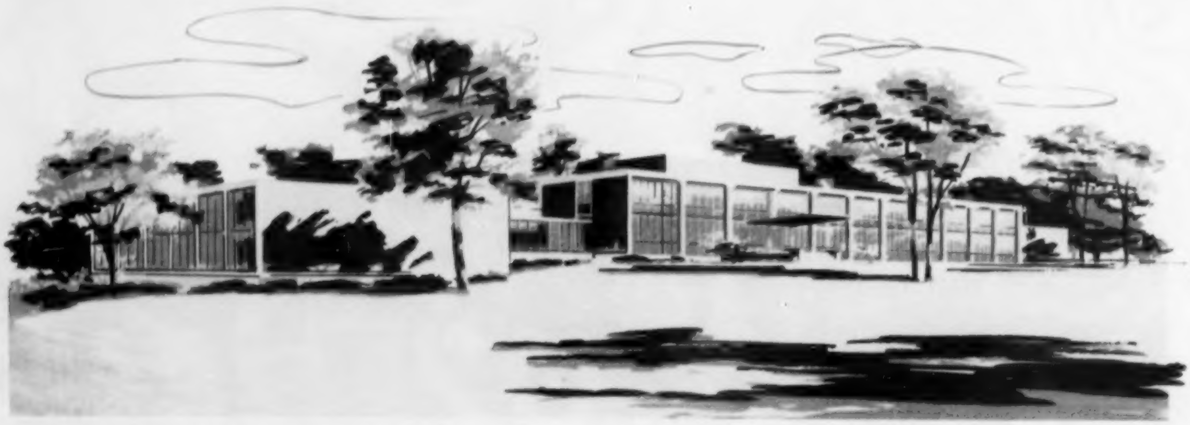
CONCLUSION

With many carbon-lined cupolas now in operation and many more projected for the immediate future, carbon definitely occupies a place in the cupola refractory scene. Moreover, the progressive trend exemplified by the type of operation in which carbon is now being used, together with the sometimes astonishing degrees of efficiency and economy reported over former linings, bears an importance out of all proportion to the number of cupolas as yet involved.

ADVANTAGES OF CARBON FOR CUPOLA LININGS

- Eliminates refractory damage by slag corrosion
- May be used with acid, basic or neutral slags without relining.
- Will not crack or spall from thermal shock
- May be quenched when hot, speeding cupola repairs
- Retains mechanical strength at high temperatures
- Does not adhere to metal or slags
- Cannot soften or melt
- Provides long, trouble-free life for extended periods of operation

UNION CARBIDE'S NEW LAB TO SEEK MATERIALS OF TOMORROW



Union Carbide and Carbon Corporation is building a new Research Laboratory at Parma, Ohio, to be managed by National Carbon Company, a Division of the Corporation.

While other major UCC research units are devoted primarily to inorganic chemistry, organic chemistry, plastics and metallurgy, the work at Parma will be in the fields of physics and the interrelation of physics and chemistry. This is an appropriate assignment for National Carbon since its present research organization is well fitted to function in these fields.

The new Research Laboratory will engage in basic, exploratory work. Much of it will be on solid state physics research in the broad abstract sense, as well as the practical investigation and design of materials for future industrial requirements. Work will be done with metallic and nonmetallic compounds of carbon, as well as analogous compounds, such as inter-metallics and semi-conductors. Activities will be directed toward specific end-products only to the extent that such products have their primary origins in the discovery of new and fundamental material-process applications. On this broad basis, the horizons of this new research operation are virtually unlimited and, consequently, unpredictable.

Among the possible far-future developments to come from studies at the new UCC Research Laboratory are materials for new and improved transistors and related electronic devices that can play a tremendously significant role in an expanding electronic world.

The key to further development of new ferrites may be found. Ferrites are complex, inorganic compounds having high permeability at low flux — they could have wide application in electronic computers and automation devices.

New refractory compounds, as well as improvements in the established materials, such as graphite, could come out of research on totally new materials and processes for this important industrial application.

Photo-sensitive materials, leading to new and more efficient methods of converting light energy to electrical energy, might be developed.

National Carbon Company's present products, such as electrodes, brushes, projector carbons, dry batteries and carbon and graphite shapes, have resulted from the application of traditional physics and the sciences of optics, electrophysical chemistry, conductivity, and surface phenomena. Research along these lines will, of course, be continued and amplified; but in this new laboratory, emphasis will be placed on the more radical approaches which the new physics may suggest.

The Laboratory will cost several million dollars, with ground improvements, buildings, equipment and furnishings, and will accommodate a staff of approximately 200 research personnel, plus clerical and service personnel.

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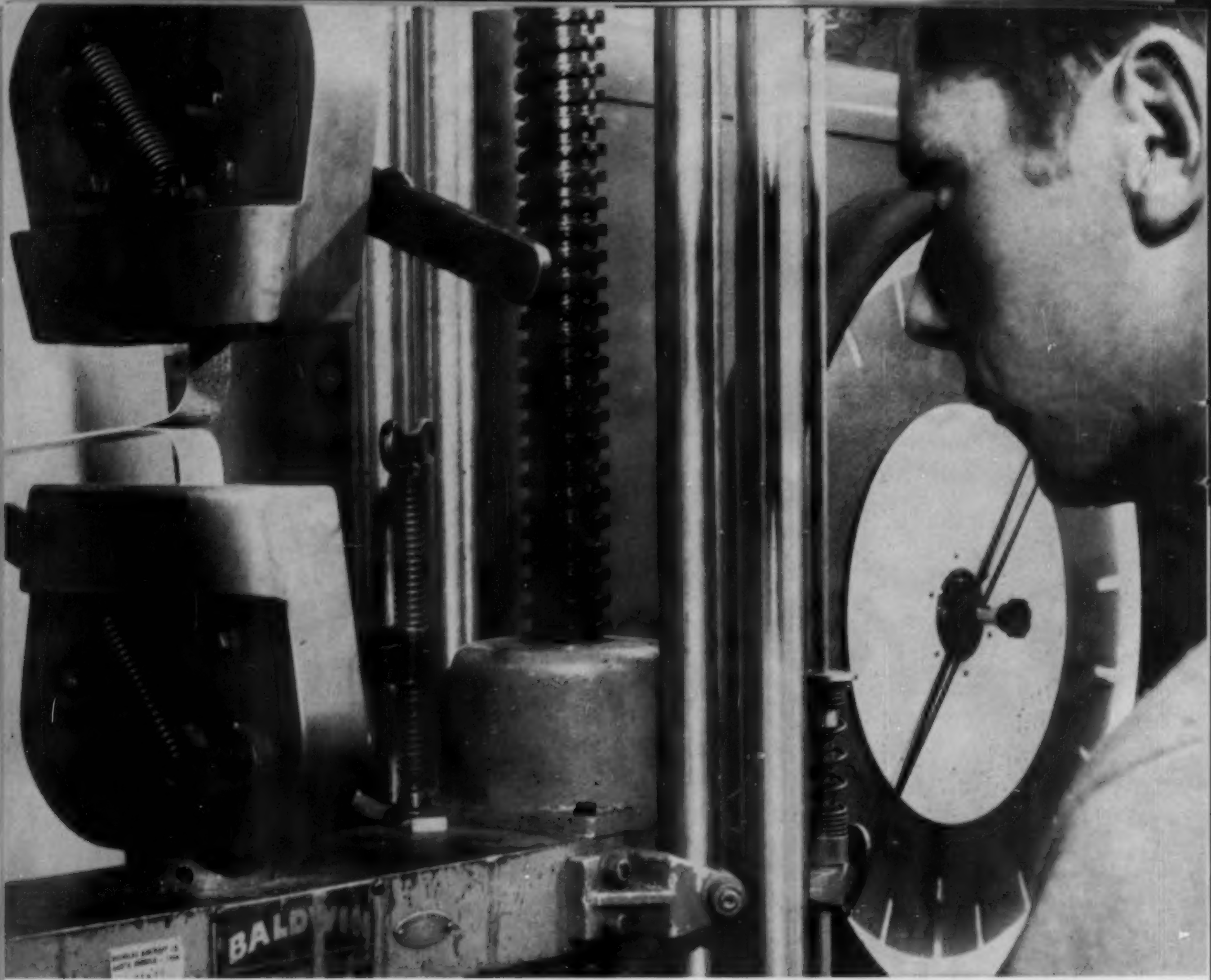

Douglas Aircraft's new tear and peel tests prove versatility of 5000-lb. Baldwin machine

Douglas Aircraft Company finds their versatile Baldwin gives accurate, flexible testing in two new tests devised by them. At their Santa Monica, California Materials Laboratory tear and peel tests on titanium sheet and metal bonding adhesives, respectively, are being run on this 5000-lb. universal machine.

The tear test is used to determine usable quality sheet before release to the factory. It also measures brittleness, formability and strength. The test is conducted on the Baldwin by applying tension loads to a specially-prepared specimen engaged in steel hooks. By pulling the ears of the specimen, tearing originates at a pre-set point produced by a notch. The load increases until reaching the force required to start the tear from the notch. Then the load drops off rapidly or slowly in relation to the brittleness or ductility of the material. The load is autographically recorded along with the strain during the test.

Their peel test operation measures tensile strength of metal bonded specimens. Test panels are gripped in the jaws of the Baldwin machine and are peeled apart at a jaw separation rate of two feet per minute, separating the bond at a rate of one foot per minute. An autographic record versus crosshead motion is obtained. The test includes measurement of average adhesive film thickness and type of failure.

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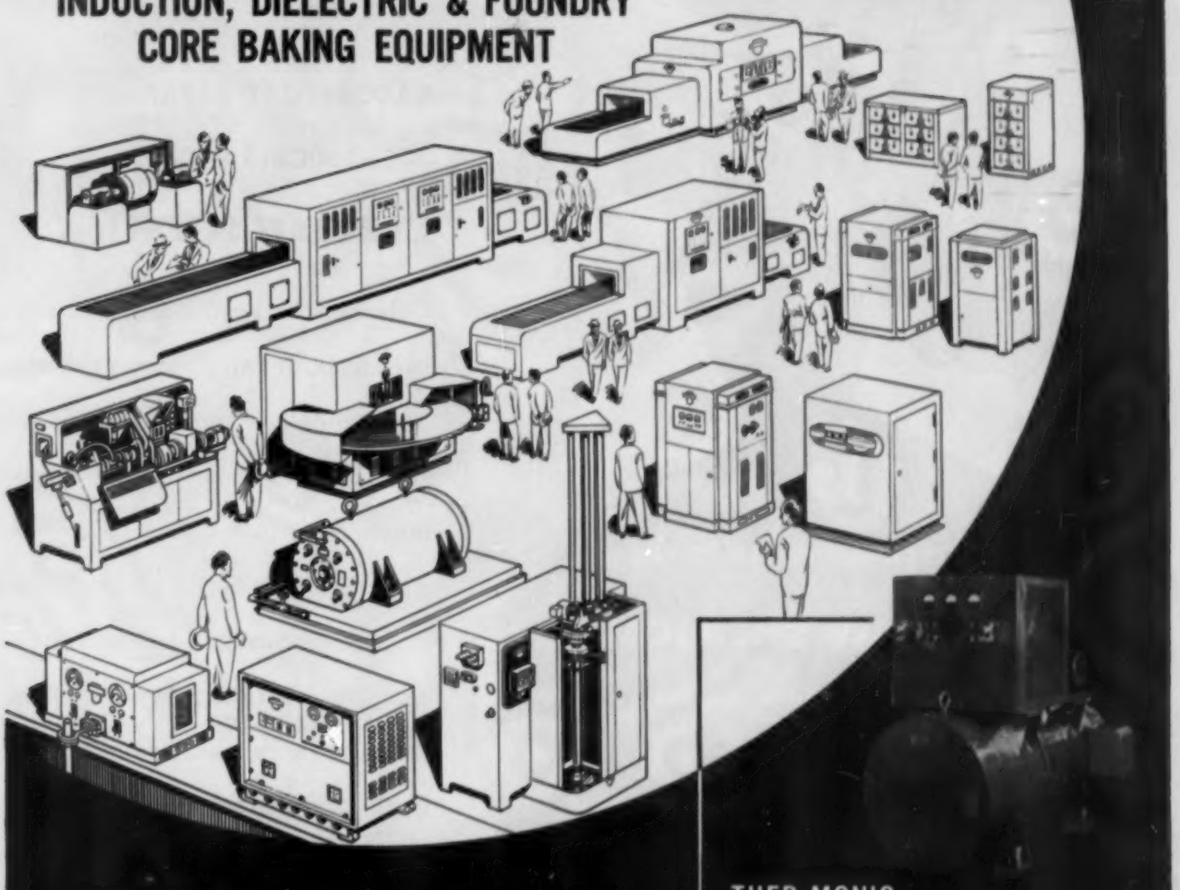

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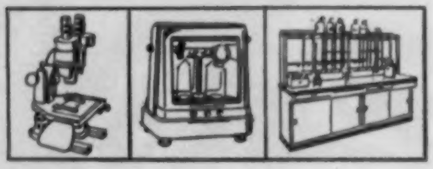
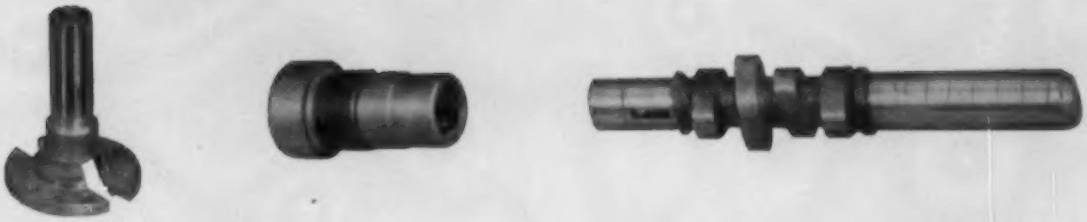
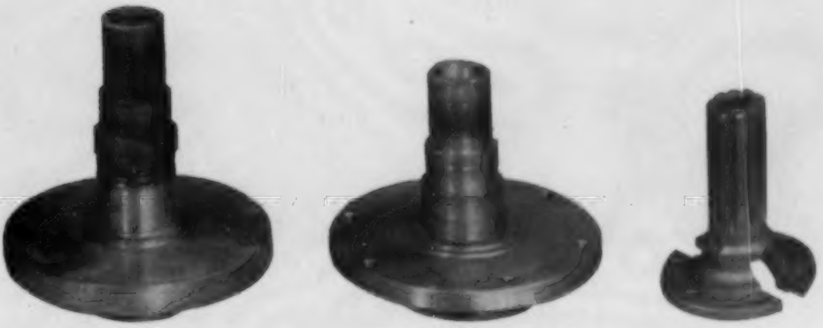




what's new ?

NUMBER 32 OF A SERIES



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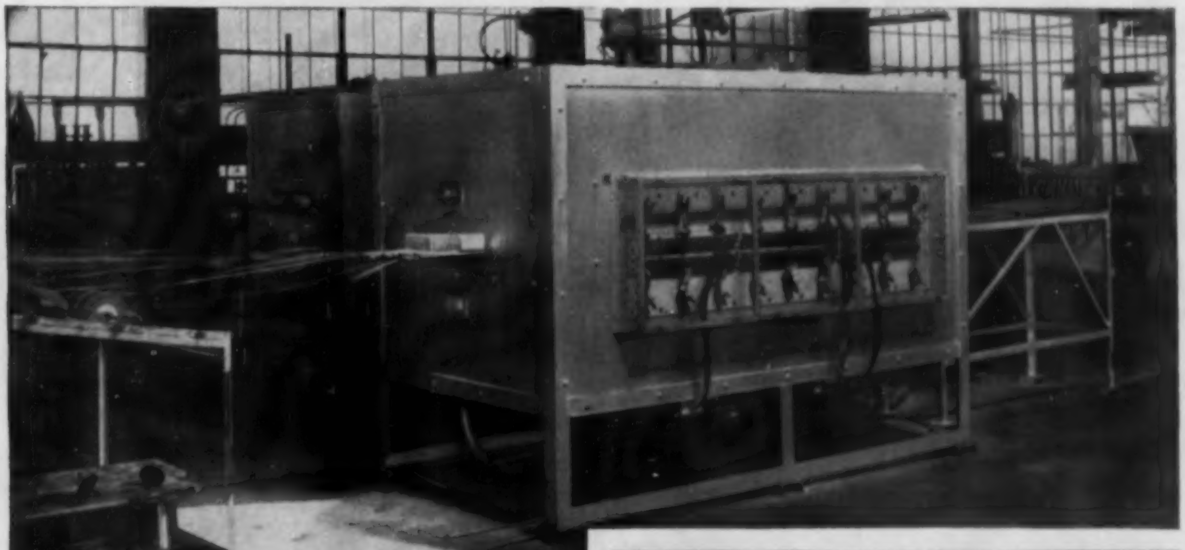

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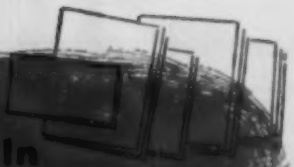

561. Alloy Steel

14-page bulletin on two chromium-nickel alloy steels. Properties, working instructions, heat treatment, recommended uses. *Carpenter Steel*

562. Alloy Steel

Data book on the selection of the proper alloy steel grades for each manufacturer's needs. *Wheelock, Lovejoy*

563. Alloy Steel

32-page book on abrasion resisting steel. Properties, fabricating characteristics, uses. *U. S. Steel*

564. Alloy Steel

68-page "Aircraft Steels" includes revised military specifications. Also stock list. *Ryerson*

565. Alloy Steel

40-page book on applications of heat treated, special alloy steel. *Jones & Laughlin*

566. Aluminum

12-page booklet on extruded shapes, tube and pipe, coiled sheet, forgings and properties of aluminum alloys. *Revere*

567. Aluminum Die Castings

Bulletin on design and manufacture of aluminum die castings. *Hoover Co.*

568. Aluminum Heat Treating

8-page Bulletin 5912 on solution heat treating, annealing, stabilizing and aging of aluminum. *General Electric*

569. Aluminum Heat Treating

Bulletin on furnaces for aging, annealing, heat treating and forging aluminum. *Morrison Eng'g Corp.*

570. Ammonia Dissociators

Bulletin on dissociating process gives advantages of ammonia as controlled atmosphere. *Sargeant & Wilbur*

571. Arc Welding

New 16-page catalog on equipment and accessories for tungsten arc welding process. *Air Reduction Sales Co.*

572. Atmosphere Cooling

Bulletin T-40 on automatic heat treating units with controlled atmosphere cooling. *Ipsen Industries*

573. Atmosphere Furnace

Bulletin on controlled atmosphere furnace. *Industrial Heating Equipment*

574. Atmosphere Furnace

12-page bulletin on electric furnaces with atmosphere control for hardening high speed steel. *Sentry*

575. Atmosphere Furnace

Information on mechanized batch-type atmosphere furnaces for gas cyaniding, gas carburizing, clean hardening or carbon restoration. *Dow Furnace*

576. Atmosphere Generator

Bulletin 430 on exothermic atmosphere generators for converting natural gas, manufactured gas, propane or butane. *W. S. Rockwell Co.*

577. Austempering

8-page booklet No. 500 on present status of austempering and martempering—development, S-curve theory, reasons for austempering and martempering. *Ajax Electric Co.*

578. Basic Materials

24-page booklet on Alundum, Crystolon, Magnorite, Norbide, zirconia, carbides, borides and other basic materials. Products made from them are listed. *Norton*

579. Bearings

4-page bulletin on plastic bearing materials. *Dixon Corp.*

580. Beryllium Copper

Bulletin 1 on available alloys, conditions, tempers and tables of sizes and properties. *Penn Precision Products*

581. Bimetal Applications

36-page booklet, "Successful Applications of Thermostatic Bimetal", describes 22 uses. *W. M. Chace*

582. Black Oxide Coatings

8-page booklet on black oxide coatings for steel, stainless steel and copper alloys. *Du-Lite*

583. Blackening Compounds

Bulletin on blackening compounds for ferrous alloys to AMS Spec. 2485. *Swift Industrial Chemical*

584. Brass

New 20-page pocket-size booklet on brass rod mill products. Weight tables, specifications and other technical data. *Titan Metal Mfg. Co.*

585. Brazing

Folder on low-temperature brazing tells how to boost brazing production. *Handy & Harman*

586. Brazing

Bulletin 124—on salt bath brazing process—shows how it is possible to substitute brass for copper and develop joints of adequate strength for most steel assemblies. *Ajax Electric*

587. Brazing Aluminum

12-page bulletin, ADR 45, on how to torch braze aluminum and strength of joints so brazed. *Air Reduction Sales*

588. Brazing Stainless Steel

Illustrated booklet, "Bright Annealing, Hardening and Brazing Stainless Steel", describes conveyor furnace and bright brazing alloy. *Sargeant & Wilbur*

589. Carbon and Graphite

20-page catalog on carbon and graphite applications in metallurgical, electrical, chemical, process fields. *National Carbon*

590. Carbon Brick

Bulletin on properties, grades, applications of carbon and graphite brick for handling corrosive chemicals and molten metals. *National Carbon*

591. Carbon Control

Technical report on instrument for control of carbon potential of furnace atmospheres. *Lindberg Eng'g*

592. Carburizing

16-page booklet on gas-carburizing processes and equipment. Discussion of suspended carburization, carbon restoration. *Surface Combustion*

593. Centrifugal Castings

Booklet on spun centrifugal castings of bronze for liners, rings, rolls, sleeves, bushings. *American Non-Gran Bronze*

594. Chromium Cast Iron

48-page book on effects of chromium on properties of cast iron. Data on production and uses. *Electro Metallurgical*

595. Cleaner

Folder gives data on metal cleaners for use with water in still-tank or spray-washing equipment. *Solventol*

596. Cleaning

Data on chemical for removing scale, rust and paint from ferrous alloys. *Kelite*

597. Cleaning

24-page booklet on use of solvent detergents for removing carbon, grease, dirt and paint. *Oakite*

598. Cleaning Aluminum

12-page bulletin on cleaning process for preparing aluminum and magnesium for welding. *Northwest Chemical*

599. Cleaning and Finishing

34 data sheets on cleaners, plating chemicals, strippers, phosphate coatings, black oxide salts, polishers. *MacDermid*

600. Coatings

Data sheet on industrial Protectox, tarnish-resistant coating for silver, silver alloys, copper, brass and gold. *Technic*

601. Cobalt Alloy

12-page booklet, "Haynes Alloy No. 25", tells of the unique properties of this cobalt-base alloy. *Haynes Stellite*

602. Controlled Atmospheres

Illustrated literature describes controlled atmosphere installations. *Gas Atmospheres, Inc.*

603. Controllers

12-page booklet on temperature controls and special purpose controllers. Operation, design, installation. *Assembly Products*

604. Copper Alloys

New 48-page book contains tables of alloys with composition, typical uses, general, working, mechanical, electrical properties, hardness, ASTM specification numbers. *Revere*

605. Copper Alloys

40-page book on eleven copper alloys. Properties, cleaning, annealing. *Seymour*

606. Corrosion Data

Data Card 160 gives comparative resistance to various corrosive media of several stainless steels. *Babcock & Wilcox*

607. Creep Testing

6-page bulletin diagrams and describes dynamic creep testing machine. *Ivy Co.*

608. Creep Testing

Bulletin RR-13-54 on new creep testing machine. *Riehle*

609. Cut-Off Wheels

Folder gives data, operating suggestions and grade recommendations of cut-off wheels. *Manhattan Rubber Div.*

610. Degreaser

40-page book on properties and use of trichlorethylene. Methods of handling and safety measures. *Niagara Alkali*

611. Degreasers

Folders on vapor and solvent degreasers describe equipment and advantages. *Ramco Equipment Corp.*

612. Degreasing

34-page booklet on vapor degreasing. Design, installation, operation and maintenance of equipment. *Circo Equipment*

613. Descaling Process

8-page bulletin on sodium hydride de-

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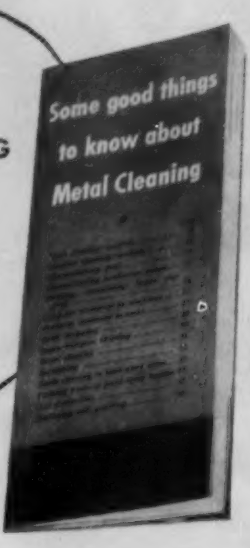

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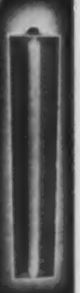

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scaling process for ferrous and nonferrous metals. *DuPont*

614. Descaling Stainless Steel
Bulletin 25 on descaling stainless steel and other metals in molten salt. *Hooker Electrochemical*

615. Design of Dies
Bulletin 75B on design of dies for upset forging. Also rules for upsetting and examples of forgings. *Ajax Mfg.*

616. Dew Point Control
Bulletin No. 21-C on instrument which indicates, records and controls dew point automatically. *Ipsen*

617. Die Casting
Booklet on "High-Speed Precision Die Casting Machines". *Reed-Prentice*

618. Die-Casting Machines
Case histories of companies using various types of die-casting machines. *Kux*

619. Die Castings
Booklet on small zinc die castings. Types that can be made. Properties of zinc die casting alloys. *Gries Reproducer*

620. Die Castings
New booklet contains standard specifications, tolerance tables and physical properties of die casting alloys. *Parker White Metal Co.*

621. Ferro-Alloys and Metals
104-page book gives data on more than 250 different alloys and metals produced by the company. *Electro Metallurgical*

622. Finishing
Two 8-page bulletins on dip tank and flow coat finishing describe processes, advantages and disadvantages of each. *Du Pont Finishes Div.*

623. Finishing
52-page book "Advanced Speed Finishing" describes equipment for deburring and finishing. *Almco Div.*

624. Flame Hardening
New 20-page catalog on flamatic hardening machines and allied equipment. *Cincinnati Milling Machine Co.*

625. Flame Hardening
Attractive literature discusses flame hardening of large ways, rolls, etc. *Detroit Flame Hardening Co.*

626. Flow Meters
Bulletin 201 on flow meter for gas used in heat treating. *Waukee Eng'g*

627. Fluoroscopy
12-page booklet on fluoroscopy for nondestructive internal inspection. Explains image amplifier. *Westinghouse Electric, Industrial X-Ray Dept.*

628. Forging Hammers
24-page brochure describes construction and use of steam drop hammers. *Erie Foundry*

629. Forgings
94-page book on die blocks and heavy-duty forgings. 20 pages of tables. *A. Finkl*

630. Forgings
Series of articles on modern forging methods. *Hill Acme*

631. Forming Dies
Bulletin No. 205 on aluminum powder reinforced epon resin casting compound for sheet metal forming dies, holding and positioning jigs and fixtures. *Metals Disintegrating*

632. Fuel Gas
Bulletin on "Pyrofax" gas for cutting, brazing, metallizing, flame hardening, carburizing and heat treating. *Pyrofax Gas*

633. Furnace Belts
44-page catalog describes metal belts for quenching, tempering, carburizing and other applications. *Ashworth Bros.*

634. Furnace Fixtures
16-page catalog on baskets, trays, fixtures and carburizing boxes for heat treating. 66 designs. *Stanwood Corp.*

635. Furnaces
Series of bulletins on controlled atmosphere, carburizing, nitriding, hardening furnaces. *American Gas Furnace*

636. Furnaces
High temperature furnaces for temperatures up to 2000° F. are described in bulletin. *Carl-Mayer Corp.*

637. Furnaces
Folder describes complete setup for heat treatment of small tools. *Waltz Furnace*

638. Furnaces
44-page Catalog 112 features furnaces for hardening, tempering, carbonitriding, forge heating, sintering, annealing and tool heat treating. *C. I. Hayes*

639. Furnaces
40-page book describes gas and electric furnaces and applications. Four basic types of atmospheres. Glossary of heat treating terms. *Westinghouse*

640. Furnaces
Bulletin on electric heat treating furnaces describes five series and accessories. *Lucifer Furnaces*

641. Furnaces
Data on luminous wall forging furnaces. *A. F. Holden*

642. Furnaces, Heat Treating
Bulletin on furnaces for annealing, normalizing, hardening, tempering, forging. *Flinn & Dreffein Eng'g*

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(3 different strength levels) .	Sheet, Bar	85,000	65,000	23
	Sheet, Bar	100,000	80,000	20
MST 6Al-4V (1)*	Bar	149,000	137,000	13
(2)	Bar	164,000	153,000	16
(3)	Bar	198,000	180,000	9
(4)	Sheet	155,000	135,000	12
MST 3Al-5Cr	Bar	155,000	145,000	13
MST 4Al-4Mn	Bar	150,000	140,000	14
MST 8 Mn	Sheet	137,000	125,000	16

* (1) 1500—½—AC
(2) 1400—½—WQ, 1100-8-AC
(3) 1700—½—WQ, 900-2-AC
(4) 1450— 2—FC to 1100-AC

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643. Furnaces, Heat Treating
12-page bulletin on conveyor furnace, radiant tube gas heated, oil or electrically heated. *Electric Furnace Co.*

644. Globar Furnaces
Bulletin 153 describes nine types of furnace using silicon carbide heating elements for temperatures to 2600° F. *Hevi Duty*

645. Gold Plating
Folder on salts for bright gold plating. Equipment needed. *Sel-Rex*

646. Graphite Electrodes
Vest-pocket notebook containing 90 pages of information on electric furnace electrodes and other carbon products. *Great Lakes Carbon Corp.*

647. Grinding Magnesium
Data on how to grind and polish magnesium alloys includes grinding wheel recommendations, procedures, dust collection and safety precautions. *Norton*

648. Hardness Tester
Bulletin on hardness tester for all regular and superficial Rockwell tests. *Kent Cliff Div., Torsion Balance Co.*

649. Hardness Tester
Literature on Brinell testing machines. *Detroit Testing Machine Co.*

650. Hardness Tester
Bulletin on Impressor portable hardness tester for aluminum, aluminum alloys and soft metals. *Barber-Colman*

651. Heat Resistant Alloy
10-page article on how to get best service out of standard grades of heat resisting alloys by proper selection. *Rolled Alloys*

652. Heat Treating
Folder on "Facts and Figures on Heat Treating Costs." *Metal Treating Inst.*

653. Heat Treating
Article on how to fixture efficiently for heat treating to increase furnace versatility and economy. Heat Treat Review, vol. 6, no. 1. *Surface Combustion*

654. Heat Treating Ammonia
24-page "Guide for Use of Anhydrous Ammonia" describes heat treating and other metallurgical uses. *Nitrogen Div.*

655. Heat Treating Fixtures
12-page bulletin on wire mesh baskets for heat treating and plating. *Wiretex*

656. Heat Treating Fixtures
Folder shows 21 examples of heat treating fixtures, trays, baskets, retorts. *Allied Metal Specialties*

657. Heat Treating Furnaces
12-page booklet on heat treating furnaces contains chronology of advances. *Holcroft*

658. Heat Treating Supplies
Data sheets on carburizing, hardening, tempering, nitriding salts, metal cleaning and rust prevention materials. *Heatbath*

659. Heliarc Welding
Pocket-sized folder contains current ranges and sizes for electrodes with table on current and number of passes required to weld various metals. *Linde*

660. High-Strength Steel
48-page book on T-1 steel, its properties and applications. *U.S. Steel*

661. High-Temperature Alloy
Property data for 21% Cr, 9% Ni heat-resistant alloy. *Electro-Alloys Div.*

662. Induction Heaters
New 12-page bulletin on low-frequency (60-cycle) induction heating furnace for nonferrous metals. *Magnethermic*

663. Induction Heating
Folder 15C8053A gives advantages of induction heating and specifications and dimensions of induction heater. *Allis-Chalmers*

664. Induction Heating
New 12-page bulletin gives descriptions, technical data on various sizes. Water systems diagrams and standard accessory equipment. *High Frequency Heating Div., Lindberg Engineering*

665. Induction Heating
60-page catalog tells of reduced cost and increased speed of production on hardening, brazing, annealing, forging or melting jobs. *Ohio Crankshaft*

666. Induction Heating
Folders on electronic induction heating generators. Case histories. *Induction Heating*

667. Induction Melting
8-page article describes use of induction melting in improved technique for rotor-casting. *Ajax Engineering*

668. Industrial Fans
Catalogs on various kinds of industrial fans — exhaust, multiblade, backward curve, for high temperatures. *Garden City Fan*

669. Industrial Radiography
Booklet gives recommendations on planning and construction of a betatron industrial radiograph laboratory. *Allis-Chalmers Mfg.*

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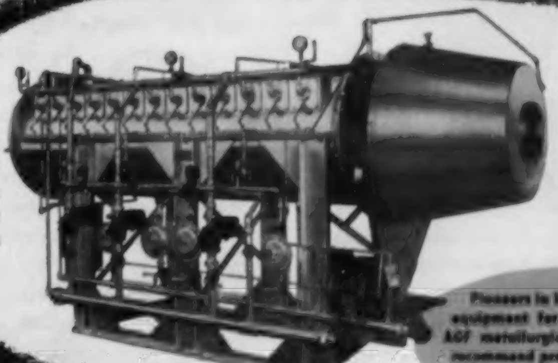

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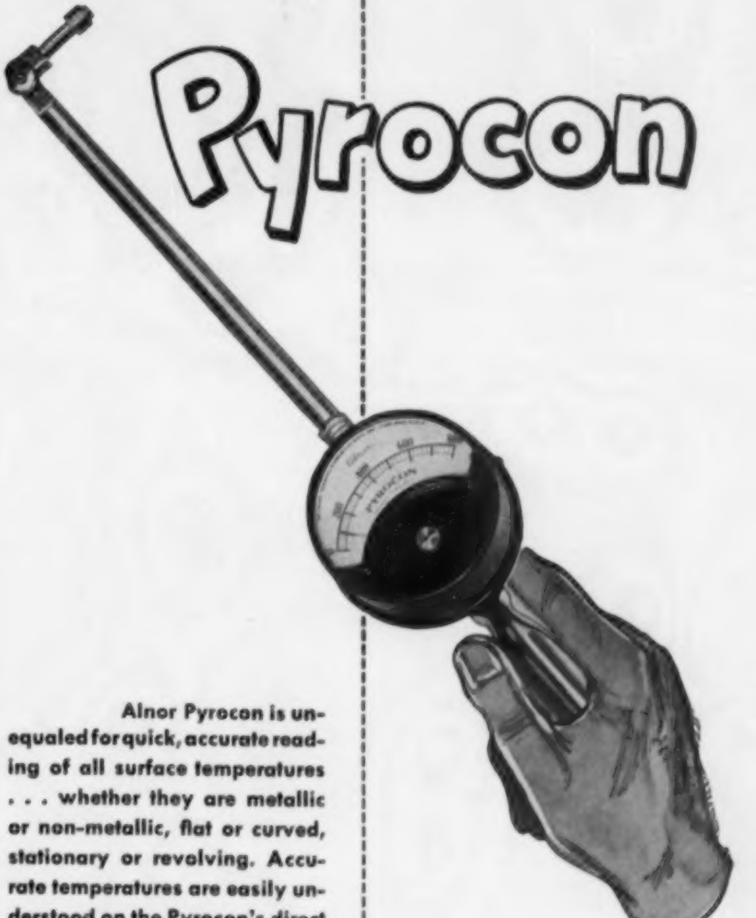

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34-page book describes 37 instruments for electrical, physical, resistance-welding, ultrasonic and other measurements. *Brush Electronics*

671. Joining Stainless
24-page booklet on various welding methods, soldering, brazing, flame cutting and arc cutting of stainless. *Crucible Steel*

672. Laboratory Supplies
Instruments and apparatus for control, research, development laboratories. *Harshaw Scientific*

673. Leaded Steel
8-page booklet on production of lead treated steels, their advantages and case histories of their use. *Copperweld Steel*

674. Leaded Steel
8-page bulletin gives chemical composition, mechanical properties and case studies showing machining production rates of Ledloy, lead bearing steel. *Ryerson*

675. Leak Detector
16-page bulletin on leak detector for location and measurement of leaks in evacuated or pressure systems. *Consolidated Vacuum Corp.*

676. Light Metal Castings
Bulletin "Creative Castings" on making castings of aluminum and magnesium. *Thompson Products, Light Metals Div.*

677. Lubricant
Literature on anti-seize molybdenum disulfide lubricant. *Bel-Ray*

678. Lubricant
Bulletin 104 on microsize powder of molybdenum disulphide lubricant. *Alpha*

679. Magnesium
42-page booklet on wrought forms of magnesium. Includes 31 tables. *White Metal Rolling & Stamping*

680. Magnesium Alloys
Loose-leaf folder of data and tables on chemical specifications, properties, extrusion, machining operations. *Brooks and Perkins*

681. Melting Furnace
Bulletin gives specifications, diagrams, performance and other technical data on Simplex melting furnaces. *Lindberg Engineering*

682. Melting Guide
Selector guide for heating, equipment and control for solder, tin and lead melting. *General Electric Co.*

683. Metal Powders
168-page catalog. B-44, on bronze and ferrous alloys. Design data, load capacities, properties, assembly procedure. *Amplex Div.*

684. Microscopes
Catalog on metallograph and several models of microscopes. *United Scientific*

685. Nickel Alloys
40-page book gives corrosion, physical and mechanical properties of Hastelloy alloys; 13 pages of fabrication data. *Haynes Stellite*

686. Nickel Alloys
Wall chart gives engineering properties of nickel alloy wire, rod and strip. Includes Monel, Inconel, Incoloy and nickel-clad copper. *Alloy Metal Wire Co.*

687. Nondestructive Testing
8-page bulletin on equipment for nondestructive testing of bars, rods, tubing. *Magnetic Analysis*

688. Nonferrous Wire
Folder gives wire gage and footage chart and data. *Little Falls Alloys*

689. Oil Quenching
8-page brochure tells in detail how carbon steel often can replace alloy steel when additive is used in the quenching oil. *Aldridge Industrial Oils*

690. Pickling Baskets
12-page bulletin on mechanical picklers, crates, baskets, chain and accessories. *Youngstown Welding & Eng'g*

691. Pickling Baskets
Data on baskets for degreasing, pickling, anodizing and plating. *Jelliff*

692. Plating Solutions
Operating manuals for plating with metal fluoborate solutions. *Baker & Adamson* See page A-111.

693. Plating Solutions
Bulletin 12 on electric heating of pickling and plating solutions. *Pyrosil*

694. Polishing Materials
20-page booklet includes samples of emery, aluminum oxide and silicon carbide papers and 12 polishing cloths. *Buehler, Ltd.*

695. Precision Casting
8-page bulletin on investment castings of various ferrous and nonferrous alloys. *Engineered Precision Casting*

696. Pyrometer Accessories
Bulletin 4181 on specifications and performance data for thermocouples. Thermocouple alloys, temperature-millivolt relationship curves, temperature conversion table. *Illinois Testing Laboratories*

697. Quench Agitation
Information on mixers and agitators, including units applicable to industrial quenching equipment. *Mixing Equipment*

698. Radiography
28-page booklet on products for industrial radiography gives exposure and processing data. *DuPont*

699. Radiography
Bulletins JR and AR on one and two million volt X-ray generator. *High Voltage Engineering Corp.*

700. Rare Earths
8-page Progress Report Number 1, "Rare Earths in Iron and Steel Melting". *Molybdenum Corp.*

701. Recirculating Furnace
Bulletin on continuous-type recirculating furnace shows design of furnace, its operation and advantages. *Industrial Heating Equipment Co.*

702. Refractory
Bulletin No. 507 on high temperature silica cement for bonding silica and superduty silica refractories. *Chas. Taylor Sons*

703. Roll Formed Shapes
24-page Bulletin 1053 on designing, forming and producing metal shapes. *Roll Formed Products Co.*

704. Roll Forming
Bulletin 854 on roll forming of cold rolled shapes. *American Roller Die Corp.*

705. Rust Preventives
12-page bulletin on water-soluble rust-preventive. *Production Specialties*

706. Salt Bath Furnaces
Data on salt bath furnaces for batch and conveyorized work. *Upton*

707. Salt Baths
Data on electric and gas salt bath furnaces. *Bellis*

708. Sand Control
32-page book on defects and troubles in foundry and how to remedy through sand control. *Claud S. Gordon Co.*

709. Selective Carburizer
Bulletin on "No-Carb" for selective carburizing and prevention of decarburizing on high alloy steels during heating for hardening. *Park Chemical*

710. Sonic Thickness Tester
Measurement of wall thickness from one side by sonic method. *Branson*

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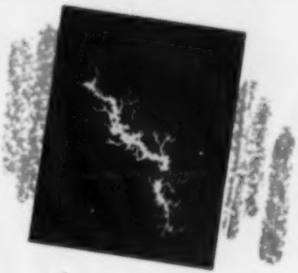
Here are 4 handy Holcroft booklets you should have in your files . . .

If you have anything at all to do with heat treating—if you are interested in stepping up production and cutting costs—if you want up-to-date information at your finger tips—here are four booklets which you should have.

1. Blazing The Heat Treat Trail With Holcroft

Here's a book which compares open-fired with controlled atmosphere furnaces. The eight different types of stock handling methods are analyzed and illustrated.



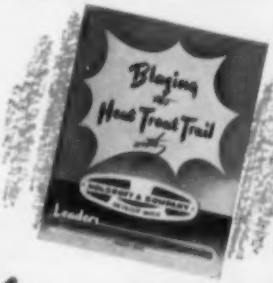
2. Holcroft And The Electric Furnace

This booklet discusses heat treating with electricity. Line drawings show how the four standard types of heating elements are used in the many different kinds of furnaces.

RADIANT-TUBE HEATING
Holcroft

3. Radiant Tube Heating

Holcroft has produced a technical treatise covering radiant tube heating for controlled atmosphere furnaces. It covers early history and the development of this type of furnace to every day use.



4. Leaders In Industrial Furnace Engineering

This book recaps current Holcroft ads. It discusses gas carburizing, carbon restoration, malleable annealing and carbo-nitriding.

Yes, there is a liberal dose of Holcroft "sell" in these books. But, beyond that, there is plenty of technical, off-the-cuff information that you should have. Write for your copy of any or all of these books—today! Holcroft & Company, 6545 Epworth Blvd., Detroit 10, Michigan.

PRODUCTION HEAT TREAT FURNACES FOR EVERY PURPOSE

CHICAGO, ILL. CLEVELAND, OHIO DARIEN, CONN.
HOUSTON, TEXAS LOS ANGELES, CALIF. PHILADELPHIA, PA.
CANADA: Walker Metal Products, Ltd., Windsor, Ontario

711. Specifications Index
28-page cross index lists copper alloy specifications of nine different Government agencies. *American Brass*

712. Spectrometer
Bulletin DR on the Atomcounter, direct reading spectrometer. *Jarrell Ash*

713. Spring Steels
Spring steel catalog offers 785 sizes of hardened and tempered spring steels, and 133 cold rolled and annealed. *Sandvik Steel*

714. Stainless Castings
20-page booklet shows how they are made, property and size data, typical applications. *Crucible Steel*

715. Stainless Castings
8-page bulletin gives recommendation charts for type of stainless to use in various corrosive solutions, under various conditions. *Waukesha Foundry*

716. Stainless Fastenings
20-page catalog of stainless steel cap screws, nuts, washers, machine screws, sheet metal screws, set screws, pipe fittings and specialties. *Star Stainless Screw*

717. Stainless Pipe
Bulletin TB-356 gives methods of bending and joining stainless pipe. Dimensions and weights of various types. *Babcock & Wilcox*

718. Stainless Steel
Slide chart. Set top at a certain fabricating operation, bottom shows rating of each standard grade. On reverse side, heat treating and corrosion data. *Carpenter*

719. Stainless Steel
16-page "Type 430 Stainless for Architects & Designers". *Washington Steel*

720. Stainless Steel
36-page Design Handbook gives properties, specifications, applications, design data on springs. *Alloy Metal Wire*

721. Stamping
New 12-page catalog on stamping, drawing, forming and heading. *Plume & Atwood Mfg.*

722. Steel
16-page booklet on special steels for industry includes stainless, electrical, silicon, and tool steels, magnetic materials, carbide metals. *Allegheny Ludlum Steel*

723. Steel 52100
New stock list on 52100 tubing, bars and ring forgings. *Peterson Steels*

724. Steel Terms
32-page dictionary of terms used in the steel industry. 180 definitions. Equilibrium diagrams, tables, figures. *LaSalle Steel*

725. Steel Treating
Bulletin on flame hardening, induction hardening, carbonitriding, nitriding, liquid carburizing. *Lakeside Steel Improvement*

726. Steel Tubing
48-page Handbook F-3 on fabricating and forging steel tubing. Bending, shaping, cutting and joining operations described. *Ohio Seamless Tube*

727. Stress-Strain Recorders
New 28-page bulletin No. 4215 on 16 standard recorders and 50 models of strain followers, for use on standard testing machines. *Baldwin-Lima-Hamilton*

728. Sub-Zero Equipment
New 12-page catalog of chilling machines and temperature testing units. *Cincinnati Sub-Zero Products*

729. Sulphur Determination
Literature on 3-min. determinator for use with combustion furnace. *Dietert*

730. Surface Pyrometer
Bulletin 168 on instrument for quick, accurate readings of surface temperatures. *Pyrometer Instrument*

731. Surface Temperature
Bulletin No. 4257 on Pyrocon, surface temperature instrument. *Illinois Testing Laboratories*

732. Tempilstiks
"Basic Guide to Ferrous Metallurgy," a plastic laminated wall chart in color. *Claud S. Gordon*

733. Testing Equipment
80-page illustrated catalog lists over 130 testing and measuring tools for laboratory and production-line use. *General Electric*

734. Testing Machines
28-page catalog on screw power universal testing machines and accessories. Construction, specifications. *Riehle*

735. Textured Metal
16-page booklet on advantages and applications of textured metal. *Rigidized Metals*

736. Textured Steel
New booklet on surface rolled patterns in steel. *Sharon Steel Corp.*

737. Tin
20-page booklet describes mining of tin and its present use by American industry. *Malayan Tin Bureau*

738. Titanium Alloy
Data on ternary alloy with 3% aluminum and 5% chromium gives physical properties, forging temperatures, high temperature characteristics. *Mallory-Sharon Titanium*

739. Tool and Die Steels
26-page book on six oil and air hardening steels for high-production tools and dies. Many uses illustrated. *Bethlehem Steel*

740. Tool and Die Steels
28-page guide to qualities and sizes available. *Uddeholm*

741. Tool Steel
36-page booklet on properties and applications of high speed steels, nonferrous cutting materials and carbides. *Allegheny Ludlum*

742. Tools
New 64-page catalog of rotary burrs, grinding points, saws, testers and other metalworking equipment. *Martindale Electric*

743. Tubing
52-page "Handbook of Seamless Steel Tubing". 26 pages of data. *Timken*

744. Tubing
Bulletin TB-357 on seamless or welded pressure tubing and pipe for subzero service. *Babcock & Wilcox*

745. Ultrasonic Cleaning
Folder on principles and methods of metal cleaning by application of ultrasonic energy. *Detrex*

746. Vacuum Melting
Bulletin on production and testing equipment for vacuum melting. Advantage. *Utica Metals Div., Utica Drop Forge & Tool*

747. Vacuum Metallizing
Reprint "High Vacuum Metallizing of Metals and Plastics". *Consolidated Vacuum Corp.*

748. Vacuum Pumps
Bulletin 400 on mechanical booster high vacuum pumps. *Kinney Mfg. Div.*

749. Vanadium in Steel
189-page book on properties of ferrous alloys containing vanadium and their applications. *Vanadium Corp.*

750. Welding
New 52-page catalog on gases, welding and cutting equipment. *Air Reduction*

751. Welding Equipment
Catalog on Cadweld process and arc-welding accessories. *Erico Products*

752. Welding Rods
New bulletin on processing of welding rod materials, master alloys and other specialized products. *Shieldalloy*

753. X-Ray Supplies
Bulletin on X-ray films and chemicals for radiography. *Ansco*

August 15, 1955

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577	598	619	640	661	682	703	724	745	
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7301 Euclid Avenue, Cleveland 3, Ohio

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Name ______________________________

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Students should write direct to manufacturers.

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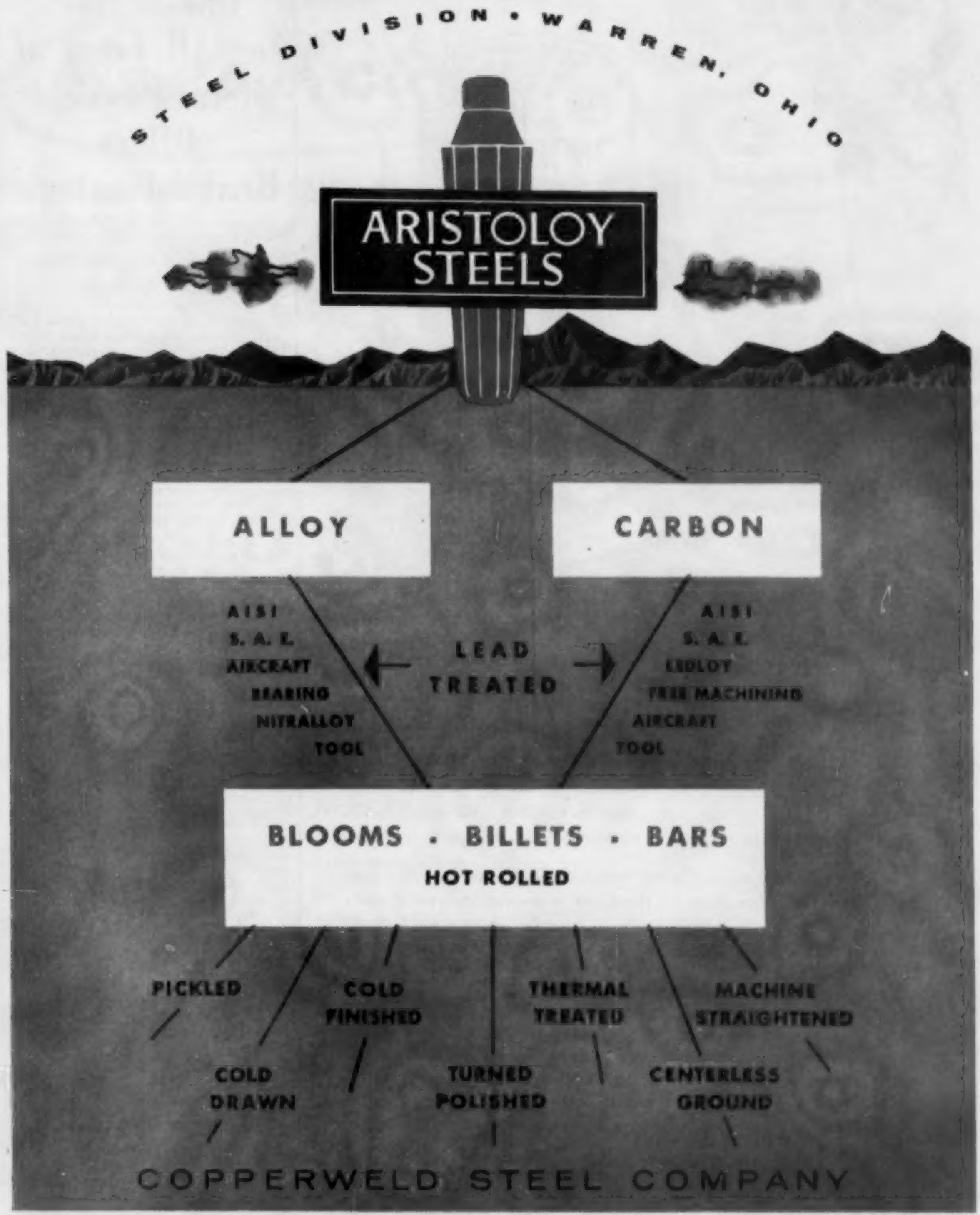

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METAL POWDER HEADQUARTERS

One Call Does It All!

A call to MD brings you direct to Metal Powder Headquarters and closer to the answer to your Powder Metallurgy problem.

For, as a pioneer in the manufacture of metal powders since 1916, MD has played a large role in the development of many of their uses in industry today as the only company which manufactures a complete line of metal powders. This has resulted in MD being the first source called on to supply an extensive line of powders for a wide range of applications.

Call on "Metal Powder Headquarters" for help on your metal powder problems. The advice and recommendations of the MD Sales Service Department are yours without obligation.

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METAL PIGMENTS
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WORLD'S LARGEST MANUFACTURER OF FINELY DIVIDED METALS

One Source For All Types of Metal Powders Offers Real Advantage

Metal Powder Headquarters provides quick means of obtaining answers to right powders to use

Regardless of the kind or type of Metal Powder required, a single call to MD (Metal Powder Headquarters) brings an answer to a Powder Metallurgy problem and the correct type of Metal Powder to meet that particular requirement.

MD has pioneered many of the major developments in Powder Metallurgy and is prepared to manufacture for you the following metal powders, in various mesh sizes. They will be glad to discuss with you the processing of "special" powders needed for your requirements.

Aluminum Powder
Brass Powder
Bronze Powder
Cadmium Powder
Copper Powder
Iron Powder
Lead Powder
Nickel Powder
Phosphor Powder
Silver Solder Powder
Solder Powder
Special Alloy Powder
Tin Powder
Titanium Powder
Zinc Powder
Antimony, Bismuth, Chromium, Magnesium, Manganese and Silicon Powders

This *one-stop* service and availability is yours by reason of the experience gained by MD through years of research and development. Today, MD is the *only* metal powder manufacturer making a *complete* line of Metal Powders.

MD Metal Pigments Widely Used

MD also manufactures Aluminum Pastes and Powders and Gold Bronze Powders for a wide range of uses such as product finishing both metal and plastics, metallic inks, etc. The decoration of many parts can be greatly enhanced with the use of such Metal Pigments. Aluminum pigmented paints are recognized for their outstanding protective qualities and can be used for priming as well as finish coats.

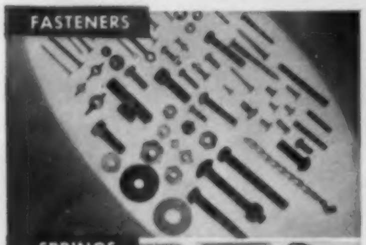
MD Oldest Shot and Grit Manufacturer

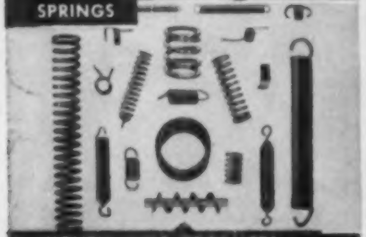
The Harrison Abrasive Division of MD is the pioneer manufacturer of Shot and Grit in this country. Harrison "Chilled" Shot and Harrison Diamond Grit are widely used in the metal trades for cleaning of castings, forgings and many metal parts. The new Harrison L/D Cut-Wire Shot meets the requirements for cleaning and peening of metal parts.

Numerous Technical Bulletins are available on request.

Basic Materials

FOR A MILLION PRODUCTS

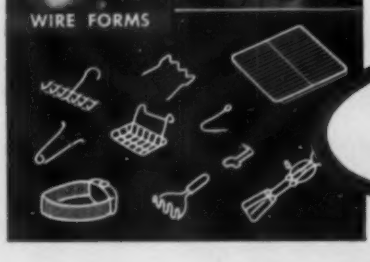

FASTENERS


SPRINGS

WOVEN WIRE PRODUCTS

ELECTRONIC COMPONENTS

WELDING & METALLIZING WIRE


WIRE FORMS

Alloy Wire, Rod and Strip . . .

Design Engineers are taking advantage of the outstanding mechanical and electrical properties and excellent formability of Alloy Wire, Rod and Strip. Results: Better products, smaller and lighter products, products that are more corrosion-resistant, more heat-resistant, more attractive —and more economical.

Alloy Metal Wire Division can supply you with high quality wire, rod and strip in Stainless Steels, Nickel Alloys and Electrical Resistance Alloys. Why not put these versatile materials to work for you?

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D-2—Nickel Alloys
D-3—Stainless Steels

FOR A BETTER DESIGN . . .
Use Wire, Rod, & Strip

FOR BETTER PRODUCT PERFORMANCE . . . *Use Alloys*

Among the alloys we fabricate, you will surely find one with just the right combination of properties for your specific application. And you can profit from the fabrication advantages and material cost and weight savings of wire, rod and strip parts and assemblies. Select the alloy you need from these three functional groups:

STAINLESS STEELS—

Alloy Metal Wire Division can provide you with more than 20 different grades of stainless steels. These include the chromium-nickel Austenitic grades with their outstanding corrosion resistance and good mechanical properties; the high chromium Ferritic grades with their high heat resistance, corrosion resistance, and outstanding cold working properties; and the lower chromium Martensitic grades which can be heat treated to obtain exceptionally high strength and hardness in addition to good resistance to corrosion and high temperatures. Stainless steel Wire, Rod and Strip are used extensively for high strength and corrosion-resistant fasteners, springs and mechanical parts and for welding wire, woven and knitted wire parts, and many other applications.

NICKEL ALLOYS—

A wide variety of Nickel alloys are also available for hundreds of electrical and mechanical applications. The excellent electrical characteristics of nickel are especially advantageous for electronic tube parts, such as grids, cathodes, support rods and pins. Monel, because of its excellent corrosion resistance and good mechanical properties, is also used for many mechanical parts, fasteners and springs.

Inconel provides the valuable combination of outstanding heat resistance, corrosion resistance and high strength required in many applications.

RESISTANCE ALLOYS—

Five grades of electrical resistance alloys are now in production in wire, rod and strip form. These are: Alray A—20 Cr, 80Ni; Alray C—15 Cr, 62Ni, bal Fe; Alray D—18 Cr, 35Ni, bal Fe; Excelsior—45 Ni, 55 Cu; and Ni—Fe alloys.

These high quality alloys find extensive applications in the electrical and electronic fields.

SPECIAL WIRE SHAPES—

You can cut costs and improve product performance with Alloy Metal's Special Shaped Wire. Almost any cross-sectional shape can be made on our wire drawing equipment. These shapes can save you tons of metal and many hours of machining time. Shaped wire can be held to close tolerances and has a smooth, tough, flaw-free surface.

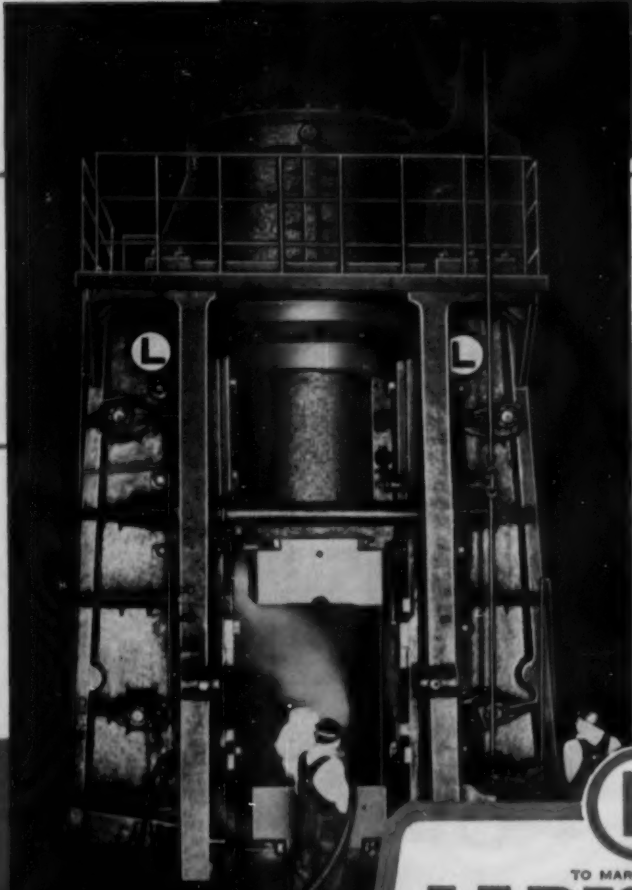
ALLOY METAL WIRE DIVISION

HKP **H. K. PORTER COMPANY, INC.**
of Pittsburgh
PROSPECT PARK, PENNSYLVANIA

2

LADISH

OFFERS GREATER LATITUDE IN THE DESIGN OF LARGE COMPLICATED PARTS



WORLD'S LARGEST FORGING HAMMER

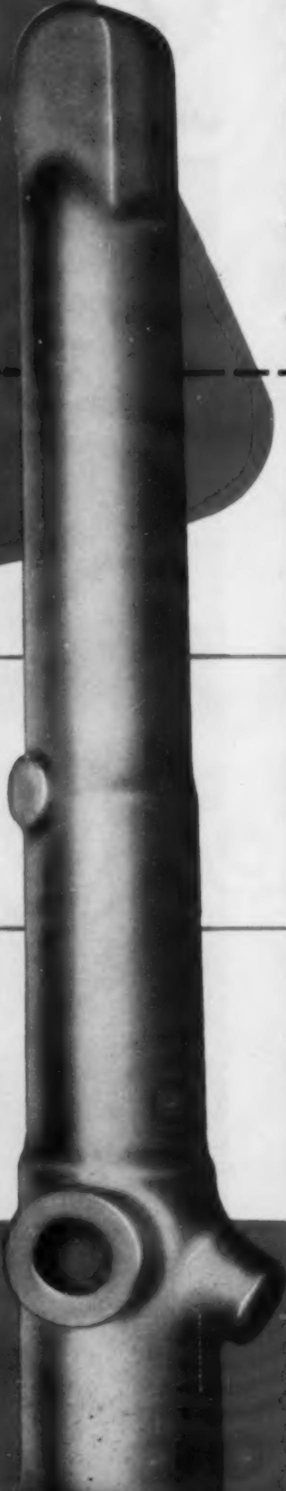
80,000 MKG counterblow forging hammer, the most powerful known in the world, is estimated to be equivalent to 100,000 pound one way steam drop hammer if such were available.

TURBINE BLADES

Forged by Ladish in Titanium and Stainless Steel Alloys to withstand tremendous pressures and temperatures without deformation.

LANDING GEAR

Outstanding example of Ladish heavy drop forgings: 8500 pounds, 132 inches in length. Drop Forging saved material and machining cost for 5000 pounds of Chromium-Nickel-Molybdenum alloy steel.



TO MARK PROGRESS

LADISH CO.

CUDAHY, (Milwaukee Suburb) WISCONSIN

Controlled Quality

DROP FORGINGS UP TO 10,000 POUNDS,
WELDED AND SEAMLESS ROLLED RINGS UP TO 80,000 POUNDS

REGARDLESS OF SIZE, CONTOUR OR MATERIAL... YOU CAN DEPEND ON LADISH

Ladish pioneering in tremendous closed-impression-die forgings offers engineers new freedom in extending the inherent advantages of the drop forging process to intricately shaped parts weighing as much as *10,000 pounds.* Drop Forging close-to-finish dimensions materially reduce metal and machining costs . . . while improvement in dynamic strength and toughness makes possible substantial reductions in dead weight . . . and higher factors of safety.

A discussion of your products with a Ladish forging engineer will provide specific data on the ultimate economy and improvement in design you can impart to your own products by specifying forgings . . . Ladish Controlled Quality forgings.

WITH CLOSED-IMPRESSION-DIE DROP FORGINGS WEIGHING UP TO 10,000 LBS.

TITANIUM PROPELLER BLADE

Again Ladish pioneers with the largest known Titanium forging produced in closed-impression dies. 40% saving in weight realized by forging this 100-inch blade in "wonder metal" Titanium.

WIND TUNNEL BLADE

2550 pound stainless steel drop forging measures 70 inches in length. Used in a wind tunnel to simulate flight speeds for jet aircraft.

DIESEL CRANKSHAFT

107-inch long Diesel engine crankshaft with 7-inch diameter journals and weighing 1772 pounds is another example of Ladish versatility in heavy drop forgings. Precise control of grain flow improves resistance to dynamic bending and torsion loads.

EXTRUDED LANDING GEAR

Developed by Ladish as an extruded forging to save valuable metal and machining time, this 44-inch long strut has an extruded hole 36 inches long, and a forged wall thickness of 1½ inches.

FOR COMPLETE SERVICE IN FORGINGS

LADISH FORGING ENGINEERS AVAILABLE FOR CONSULTATION ON USE OF FORGINGS TO IMPROVE PRODUCT DESIGN.

LADISH CO.
Cudahy, Wisconsin

We're interested...have Ladish Forging Engineer call to discuss application of forgings in our products.

Name Title

Company

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Our Products MP

Could You Use A 200% Production Increase?

A 200% Increase? Sounds incredible, but actually many users of Allis-Chalmers induction heaters report *much greater* production boosts in their brazing, soldering, hardening, annealing, and heating for forging operations.

Increased production is only one of the many profit-building benefits derived from processing with Allis-Chalmers induction heaters. Better product quality, greater uniformity, fewer rejects and less material waste are all part of the remarkable efficiency and economy made possible by this modern equipment.

The Allis-Chalmers induction heater can do your job better, faster and at less cost than your present method. Read what it has accomplished in processes similar to yours:

SOLDERING

In this operation an Allis-Chalmers induction heater soft solders oil-gauges at the rate of one every two seconds. User reports a production increase of 200% and lower costs.

ANNEALING

Twenty-four hundred brake arms are annealed every hour on this Allis-Chalmers induction heater. Set-up is automatic, operator merely loads fixture and induction heater does entire job.

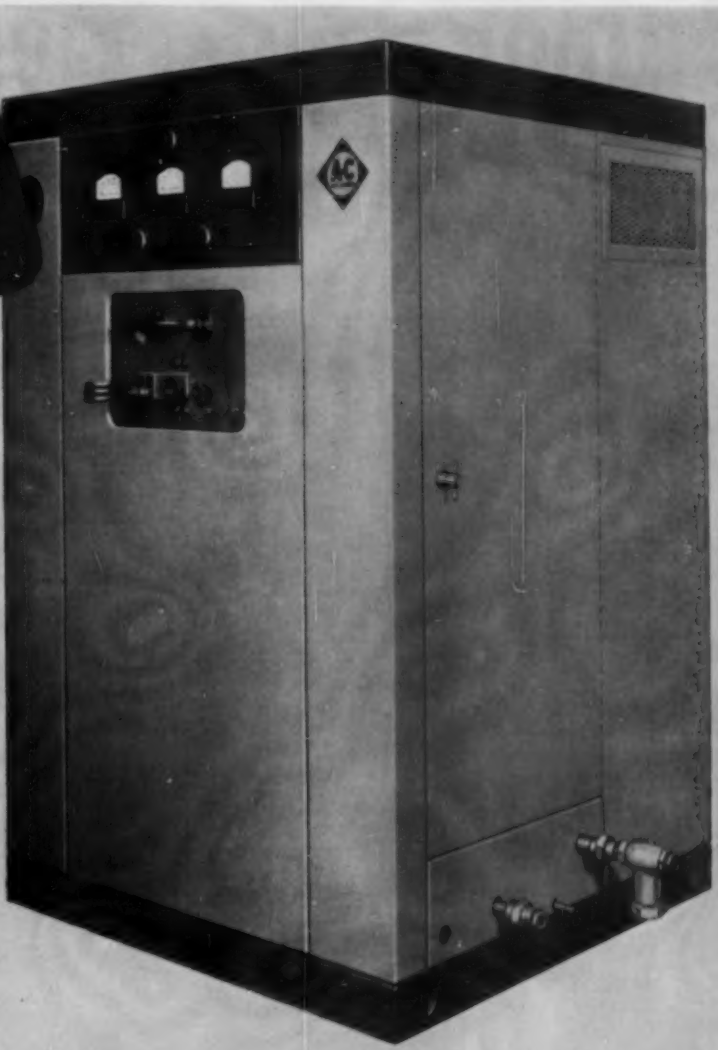
BRAZING

This job is one of brazing shrouds to blade tips in a turbojet assembly. By switching from hand brazing methods to Allis-Chalmers induction heating, *brazing time was cut in half.*

Ask for Induction Heating Information Packet

ALLIS-

ALLIS-CHALMERS
Induction
HEATER
10 to 100 KW



- High Production
- Fast Heating
- Low Heat Loss
- Minimum of Rejects
- Positive Control
- Low Maintenance
- High Quality Product
- Easy Cleaning

NEW 25 Kw Unit Air Conditioned

Air taken in through filter to cool components maintains an internal pressure higher than atmospheric pressure. Contamination of mechanical and electrical parts is prevented by outward seepage of air; maintenance and cleaning are reduced.

HARDENING

Here trimmer blades are being hardened at the rate of 2250 per hour with an Allis-Chalmers induction heater (old rate 400). Manufacturer cut costs hardening 14 totally different parts.

No Extras Needed

Output circuit developed by Allis-Chalmers eliminates need for extra output transformers or capacitors. Changing from one type of job to another is merely a matter of changing work coil.

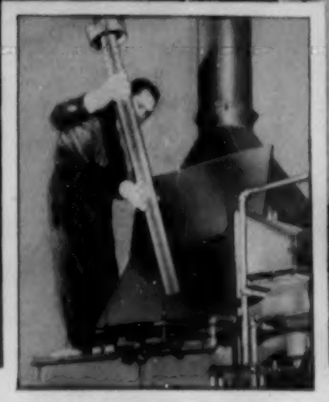
For complete information on units to fit any application requirement, contact your A-C district office or write Allis-Chalmers, Milwaukee 1, Wis.

A-4813

CHALMERS

A-C ALLIS-CHALMERS

MORE FURNACE VERSATILITY



Lindberg radiant tube is easy to change. Just turn off furnace, lift old tube out and put in new tube.

These are two of the three Lindberg gas-fired radiant tube carburizing and carbonitriding furnaces recently installed by an internationally known maker of farm machinery. With these furnaces 75% of parts are carbonitrided and 25% carburized. In addition, some bright annealing is done and the versatile Lindberg units can easily be converted for other heat treating applications.

Lindberg Vertical Radiant Tube Great Advance in Heat Treating Furnaces

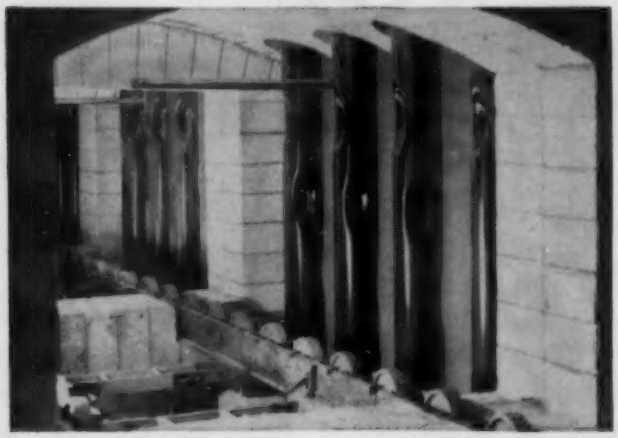
When metal needs heat, Lindberg furnaces with the new Lindberg lightweight vertical radiant tube offer a better way to apply it. Industry the world over is finding that Lindberg furnaces with this new vertical tube provide a versatility no other type of furnace can give. Carbonitriding, carburizing, carbon restoration, bright hardening or annealing and normalizing are all possible with only minor adjustments.

Here are some other exclusive advantages. Lindberg furnaces include a built-in pitless quench tank. Uniform case depth is assured because each charge automatically remains at heat the same length of time. A built-in purge chamber receives work loads for purging prior to heating.

Whatever type of furnace fits your production needs, from gigantic continuous pusher-type to the small manual batch-type furnace, Lindberg engineers can develop exactly the right equipment for you.

This three-row pusher Carburizer, with vertical radiant tubes between each row, was built for a large automobile manufacturer.

WITH LINDBERG RADIANT TUBES

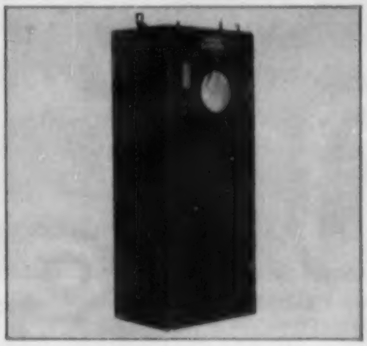


Here you can see the unique "dimpled" design of the new Lindberg vertical radiant tube. Installation is a Lindberg continuous pusher-type gas-fired carbonitriding furnace.

Revolutionary new development

The development by Lindberg of the lightweight, easily-changeable vertical radiant tube (patent pending) is one of the most significant improvements ever made in industrial furnace design. It eliminates the bulk and bend problems of the old-fashioned horizontal tube and the uneven heat patterns inherent in earlier vertical tubes. The secret lies in the new Lindberg tube's "dimples". Here's how they work—in the radiant tube a central stream of mixed air-and-gas is surrounded by a cylindrical stream of air alone and combustion occurs in the area between these two streams. The "dimples" create eddies in the streams accelerating combustion and maintaining even temperatures along the entire length of the tube. If you aren't fully familiar with this revolutionary development ask us, or your nearest Lindberg Field Engineer about it.

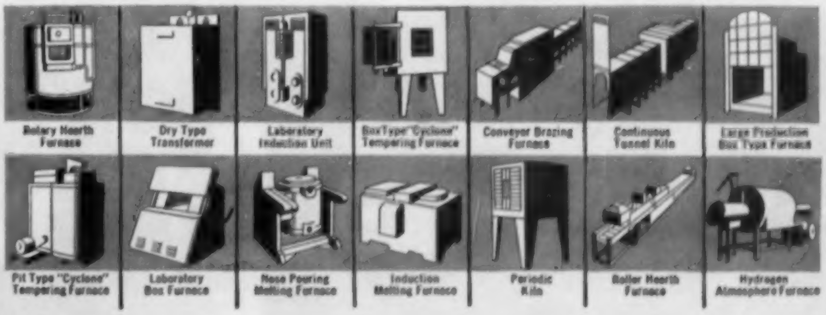
This newly-designed Lindberg Hyen generator is used with Lindberg radiant tube furnaces to supply the most exacting atmospheres needed for any heat treatment.



Here is the new Lindberg Carbotrol unit which automatically controls the carbon potential of furnace atmospheres provided by the Lindberg Hyen generator.

For the final step in heat treating, the famous Lindberg cyclone tempering furnace, for 20 years the standard of furnace performance. Pit or box type available

Lindberg manufactures many kinds of equipment in the industrial heating and related fields. A few of these are symbolized here. If you are interested in any of these please write us for the specifics on them, or get in touch with your nearest Lindberg Field Engineer. (See your classified telephone book.)


Rotary Hearth Furnace
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MODERN HEAT PROCESSING

TO SPEED OUTPUT of steel strip, G-E engineers co-ordinated this huge G-E electric furnace with the drive system for a continuous cleaning and annealing tinplate line. This system approach helped operators get 30-tons-per-hour production.

Engineers "turn on the heat" to

TO CUT ANNEALING TIME by 75 per cent for a large producer of malleable iron castings, G-E engineers "packaged" a complete annealing system—including furnaces, power equipment, and auxiliaries. Operating costs were reduced by 50 per cent.

G-E ENGINEERS E. W. Cunningham (left), General Manager, Industrial Heating, and H. M. Webber, heating application engineer, check an assembly part to be processed in a new copper-brazing furnace being installed in an automotive plant.

TO SAVE PROCESSING TIME in manufacture of textile-shrinking machinery, G-E engineers used Calrod* heaters for easier installation, better temperature control.

*Reg. trade-mark of General Electric Company

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shorten your processing cycles

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G-E engineers have co-ordinated electric furnaces into steel-mill drive systems to anneal strip continuously—at 1000 feet per minute. In metal-working plants, they have applied induction heaters to improve product quality—often cutting processing costs up to 80 per cent. And they have helped hundreds of machinery manufacturers build a variety of heating devices into equipment for greater reliability, faster operation.

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You can get other steel as strong as "T-1." You can get steel as tough as "T-1." You can get steel that is as easy to fabricate, as resistant to abrasion. But nowhere, in any material, can you get the *combination* of strength, toughness, weldability, and abrasion resistance that you get in "T-1" Steel. This combination ideally suits "T-1" to many heavy-duty applications. You can use it to improve performance, lengthen service, and reduce the cost of equipment such as pressure vessels, mining and excavating machinery, truck frames, bridges, towers, and rotating machinery.

Great strength. "T-1" brings you a minimum yield strength of 90,000 psi., a minimum tensile strength of 105,000 psi., combined with ease of fabrication. It has excellent creep rupture strength up to 900°F. Use this strength to increase the dependability or reduce the size of heavy-duty parts. Although "T-1" is a quenched and tempered steel, welding and flame-cutting do not affect its strength levels. And properly made welds develop the full strength of the parent metal.

Unmatched toughness. "T-1" Steel has demonstrated in actual field tests that it can withstand impacts as high as 2,000,000 ft. lbs. at temperatures as low as 38° below zero F. Use it to increase the durability, and cut maintenance and repair costs of equipment that must operate outdoors in the coldest winter weather.

Ease of fabrication. You will find that you can build some types of big, heavy-duty equipment at less cost with "T-1" Steel because you can fabricate it either in the shop or field. "T-1" doesn't require pre- or post-heating when it is flame-cut or welded; so that you can fabricate *anywhere* that is most convenient and economical, regardless of the availability of heat-treating equipment.

AVAILABILITY

USS "T-1" Steel is produced primarily as quenched and tempered plates. It is also available in bar or semi-finished forms, forgings, and some structural shapes. When furnished in the hot-rolled or normalized condition, for subsequent hot working such as forging, the end product must be quenched and tempered by the customer to develop full mechanical properties.

USS "T-1" Steel, because of its versatility, serves many markets and customers. This enables United States Steel to combine orders, to reduce problems involving quantity, to minimize the number of grades, and to provide superior quality and service on USS "T-1" plates. This improved availability is important today to all alloy plate consumers. It ensures a minimum capital investment, reduces expensive inventories, and speeds ordering and delivery. These factors alone can make USS "T-1" Steel the lowest cost alloy plate steel in the long run.

USS "T-1" steel plate is normally supplied in thicknesses from ½" to 6", in a wide range of widths and lengths. For some applications, it can also be furnished in lighter gauges—as low as ¼".

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USS "T-1" CONSTRUCTIONAL ALLOY STEEL

USS

UNITED STATES STEEL

...USS "T1" STEEL

How to fabricate

WELDING

1. Use a low hydrogen coated electrode. When such electrodes are used, welding may be performed without preheating with no hazard of underbead cracking. If cellulose coated electrodes are used, they will probably cause underbead cracking unless preheating is employed.

2. Use AWS 12015 electrodes if 100% joint efficiency is necessary and if stress relieving is not going to be done. If stress relieving is necessary, the AWS 12015 rod must *not* be used because the weld metal deposited by this rod, even though strong and safe in the "as-welded" condition, becomes embrittled when stress relieved.

   Recently an electrode has been developed which can be rated as E-11016 and which is now available. This electrode will develop 100% joint efficiency when used for welding USS "T-1" Steel and does not become embrittled when stress relieved.

3. Use an AWS 9015 electrode of the manganese-molybdenum type when welding must be followed by stress relieving. This rod deposits weld metal which will not develop the full strength of the base metal, so 100% joint efficiency cannot always be attained. With properly designed joints, an efficiency of 90% may be realized. Stress relieving of weldments made of USS "T-1" Steel is not generally considered necessary, because such weldments are tough in the "as-welded" condition. Stress relieving may be necessary under certain conditions in which stress corrosion is involved or where dimensional stability during machining is a factor. Stress relieving temperatures should not exceed 1150° F.

4. Some work has been done on automatic welding of USS "T-1" Steel. A semi-automatic gas shielded arc and also an automatic submerged arc method have been used successfully. Information concerning such processes may be obtained upon request.

GAS-CUTTING

Quenched and Tempered USS "T-1" Steel may be readily gas-cut without resorting to special treatments to avoid cracking. Because of the alloy content, the gas-cut edge will, of course, be considerably harder than the rest of the plate. For this reason it may be desirable to preheat to facilitate subsequent edge machining. For this purpose, 350° F will be adequate. If preheating is not employed, the resulting edge will be hard but tough and free of cracks.

Gas-cutting of USS "T-1" Steel in other than the quenched and tempered condition should be avoided.

Flame-cutting USS "T-1" Steel plates without preheat produces a hard, tough edge. The hardness of this edge may reach 400 BHN. That this edge is tough even at this high hardness level has been demonstrated by making bend tests of specimens with raw flame-cut edges. Such tests, plus visual examination of many flame-cut USS "T-1" edges have shown that preheat is not necessary to prevent cracking.

COLD FORMING AND BENDING

Many applications of USS "T-1" Steel which involve cold bending and forming have been made. No particular difficulties have been encountered. Because of the high yield strength of this steel, it is necessary to use considerably more force than would be needed to bend comparable sections of ordinary steel. The use of the largest possible bending radius is desirable. The suggested minimum bending radii for plates up to 2" thick (with axis of bend transverse to final rolling direction):

Thickness	Min. Radius
½" to 1"	2T
Over 1" to 2"	3T

Bending with the axis of the bend parallel to the final direction of rolling should be avoided where possible.

Heavier plates require considerably more power. Very little cold bending has been done on USS "T-1" Steel plates over 2" thick. However, a few such applications have been made and it has been demonstrated that heavy plates can be bent if large enough radii are employed.

MACHINING

The machining practices used on USS "T-1" Steel should be the same as those employed on steels of similar hardness (approximately 275 BHN). Large tonnages of alloy steel have been machined at this hardness level with no particular difficulties. All of the normal machining operations have been carried out by users of USS "T-1" Steel. As compared to carbon steel, lower rates and shorter tool life must be expected in line with the increased hardness.

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For Blast Furnace Operations

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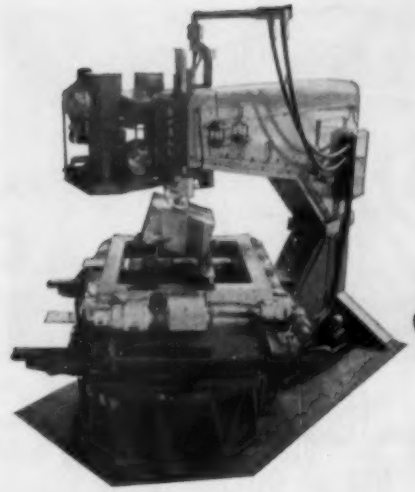

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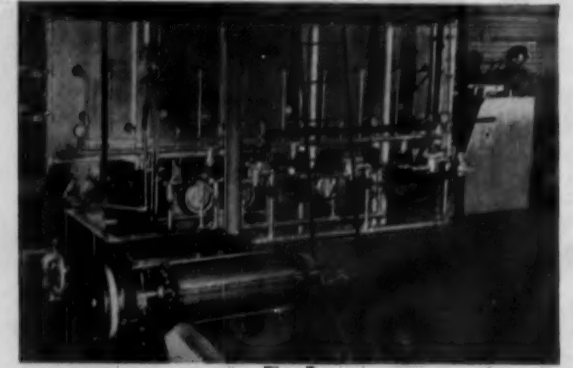

Fig. 1

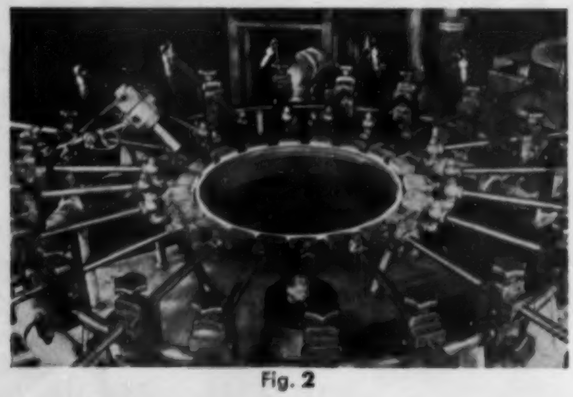

Fig. 2

An MTI commercial heat treater is located near you and is ready to serve your needs by performing "Custom-tailored" heat treating operations.

Because all members of the MTI are specialists with complete service facilities centralized in one plant, they are equipped to offer you a variety of heat treating processes—atmosphere hardening, carburizing, nitriding, annealing, cyaniding, etc.

For example, Fig. 1 shows an installation of a shaker hearth furnace with a continuous automatic quenching tank and a conveyor to a washing machine.

Fig. 2 illustrates a gas flame hardening unit featuring accurate temperature control and using two semi-circular gas manifolds mounted on movable carriages with 20 or more burner heads.

A further example of versatile and dependable equipment found in a commercial heat treating plant is seen in Fig. 3. The specially designed furnace conveyor belt carries over 35 lbs. per sq. ft. in normal service and sometimes as much as 5000 lbs. are loaded on it with pieces ranging from ½ lb. to 100 lbs. and temperatures up to 1650°.

Possessing such equipment together with many other specialized facilities and employing the trained personnel with technical knowledge and experience is the business of the commercial heat treater. Teamwork between you and the commercial heat treater can cut your costs.

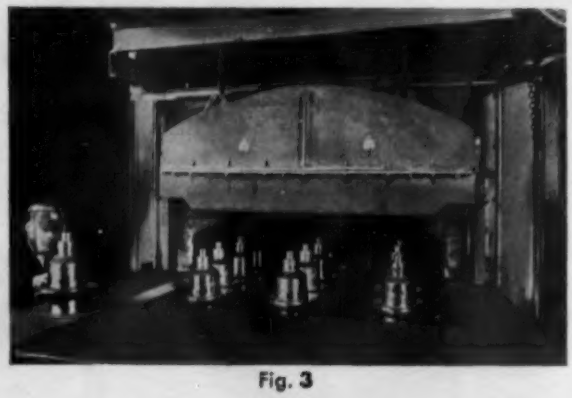

Fig. 3

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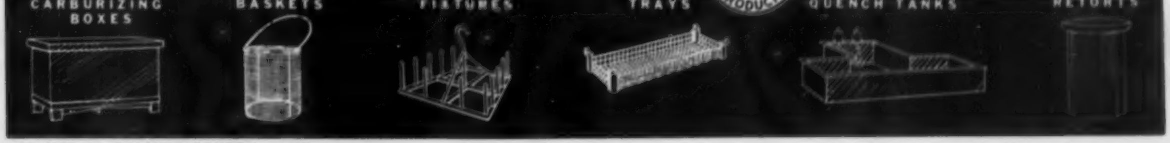

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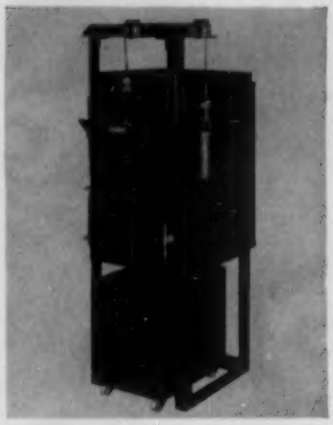

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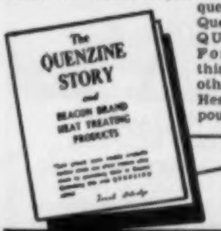

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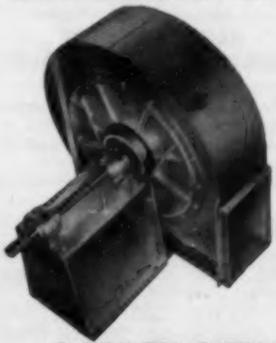

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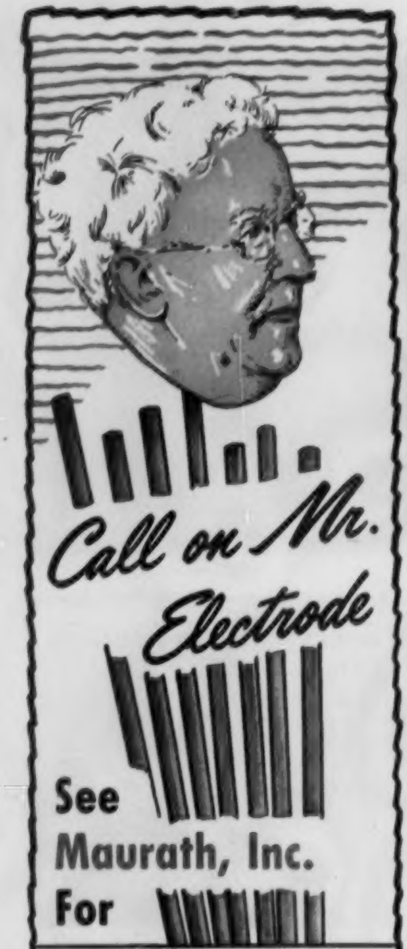

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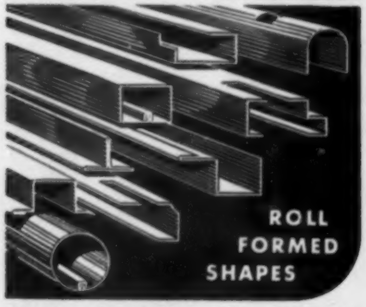

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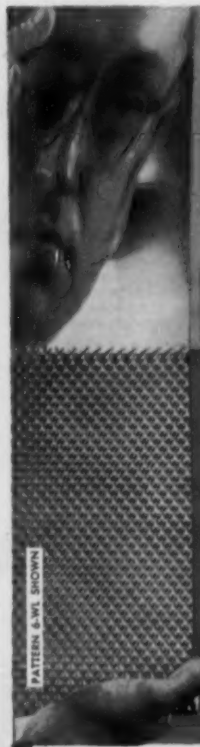

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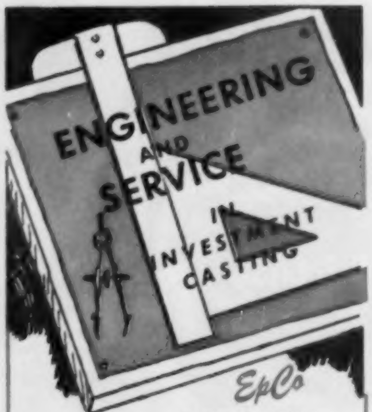

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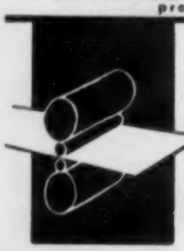

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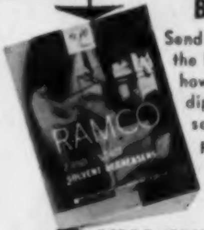

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without scratch brushing or buffing!

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CIRCO VAPOR DEGREASERS—large or small—automatic or manual operation

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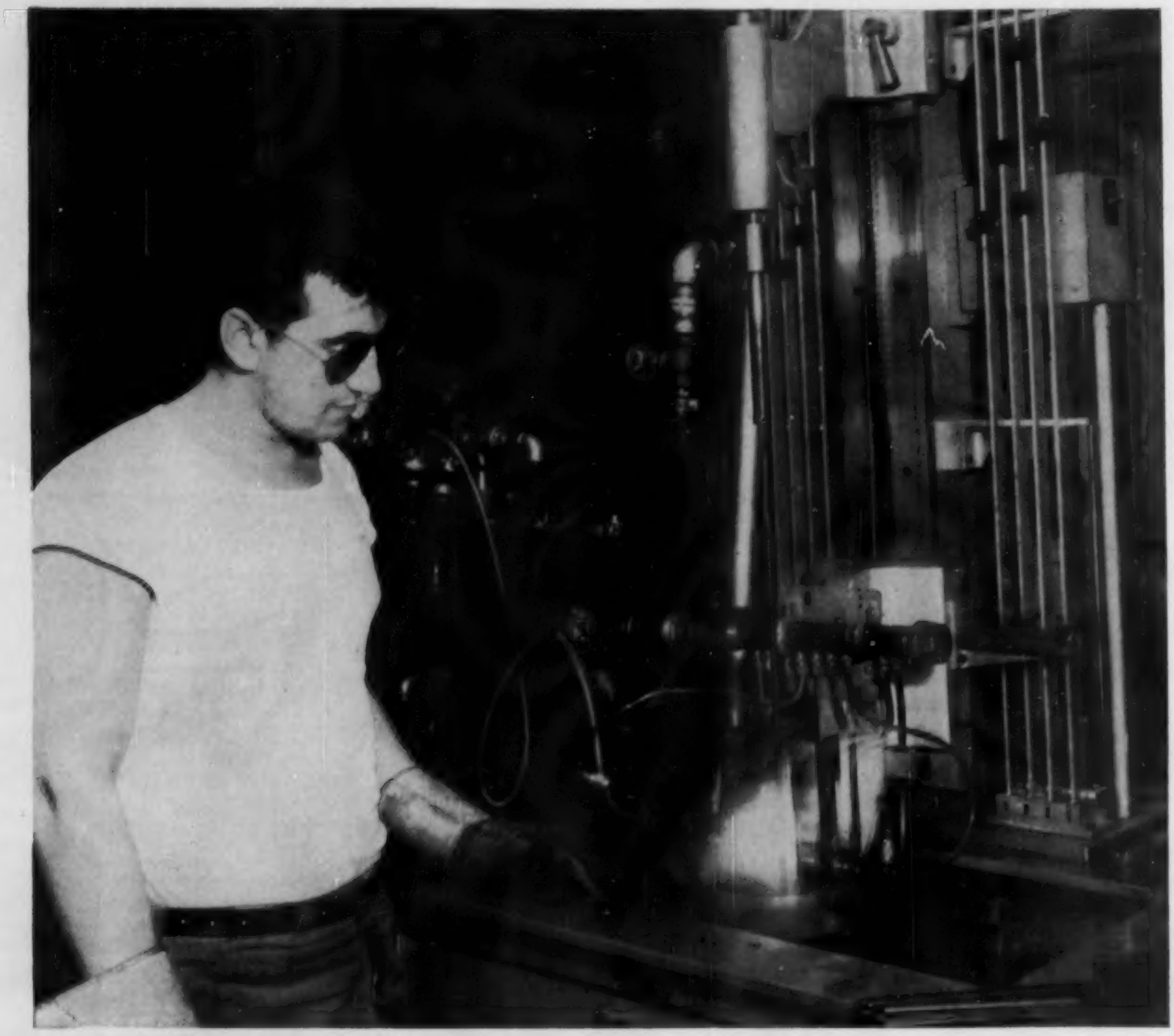

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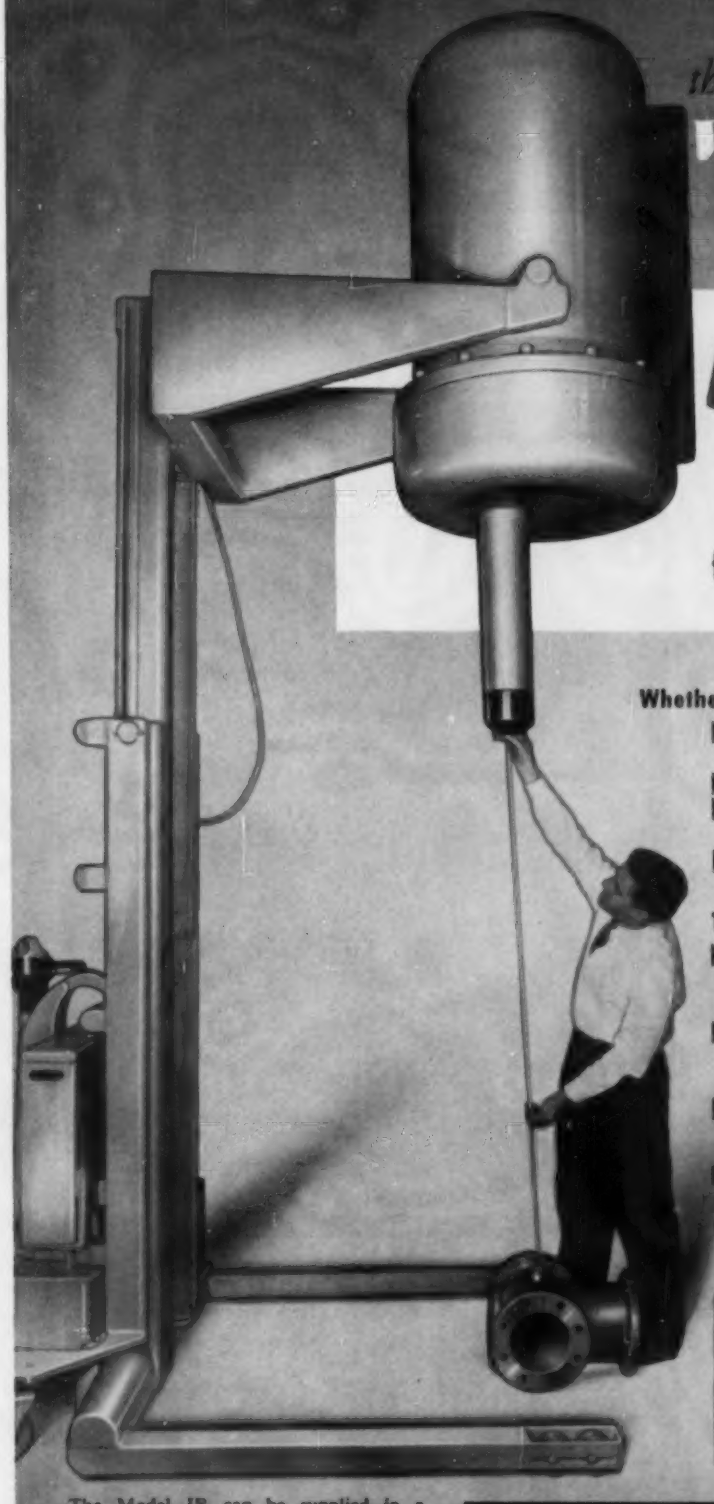

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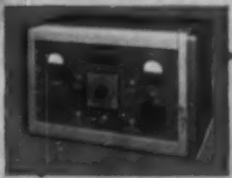

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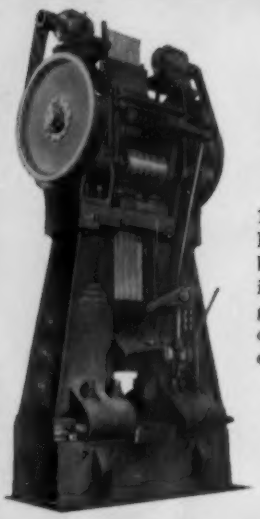

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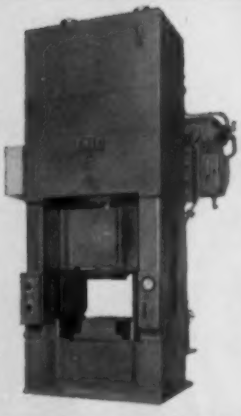

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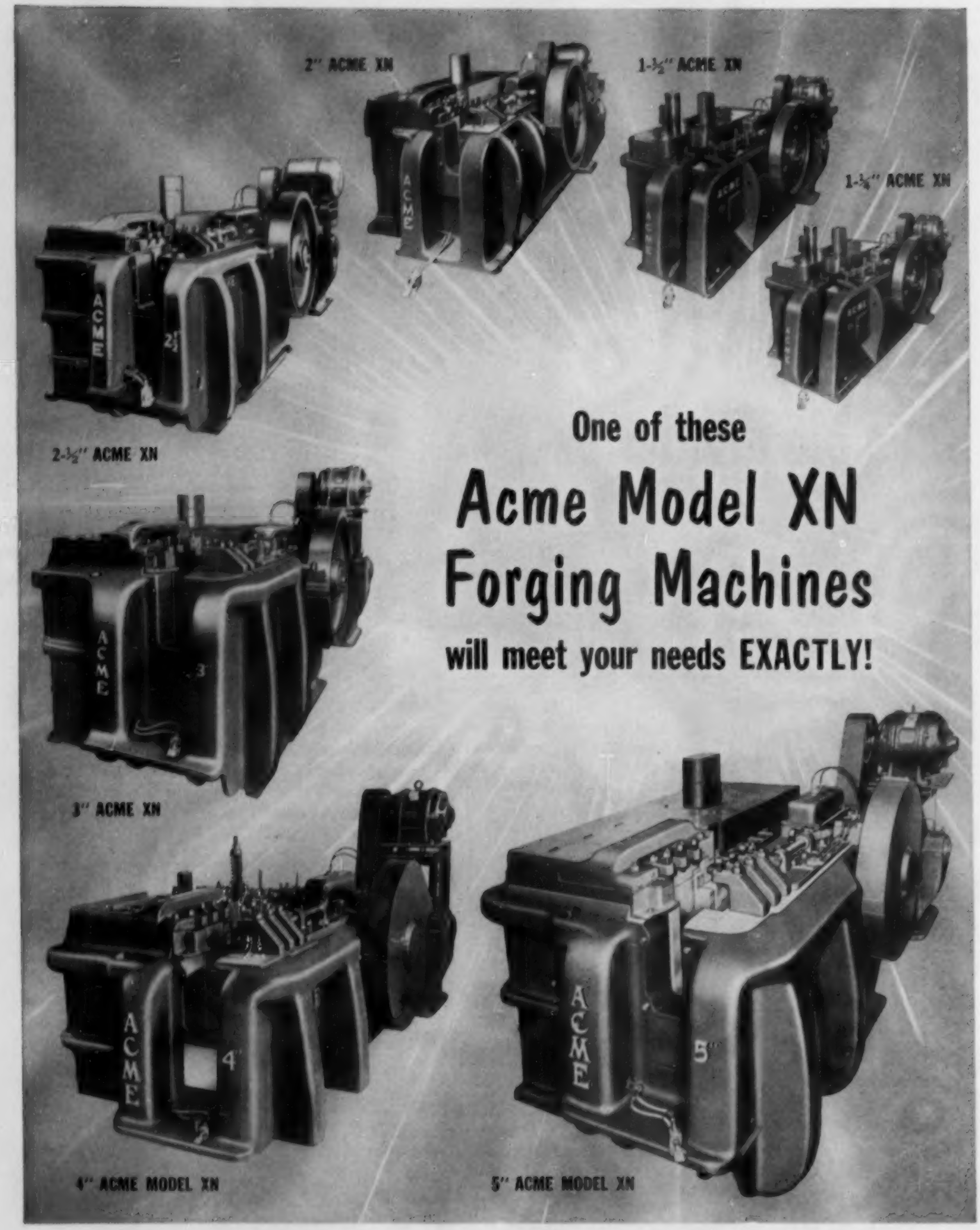
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UP TO

23,000 POUNDS

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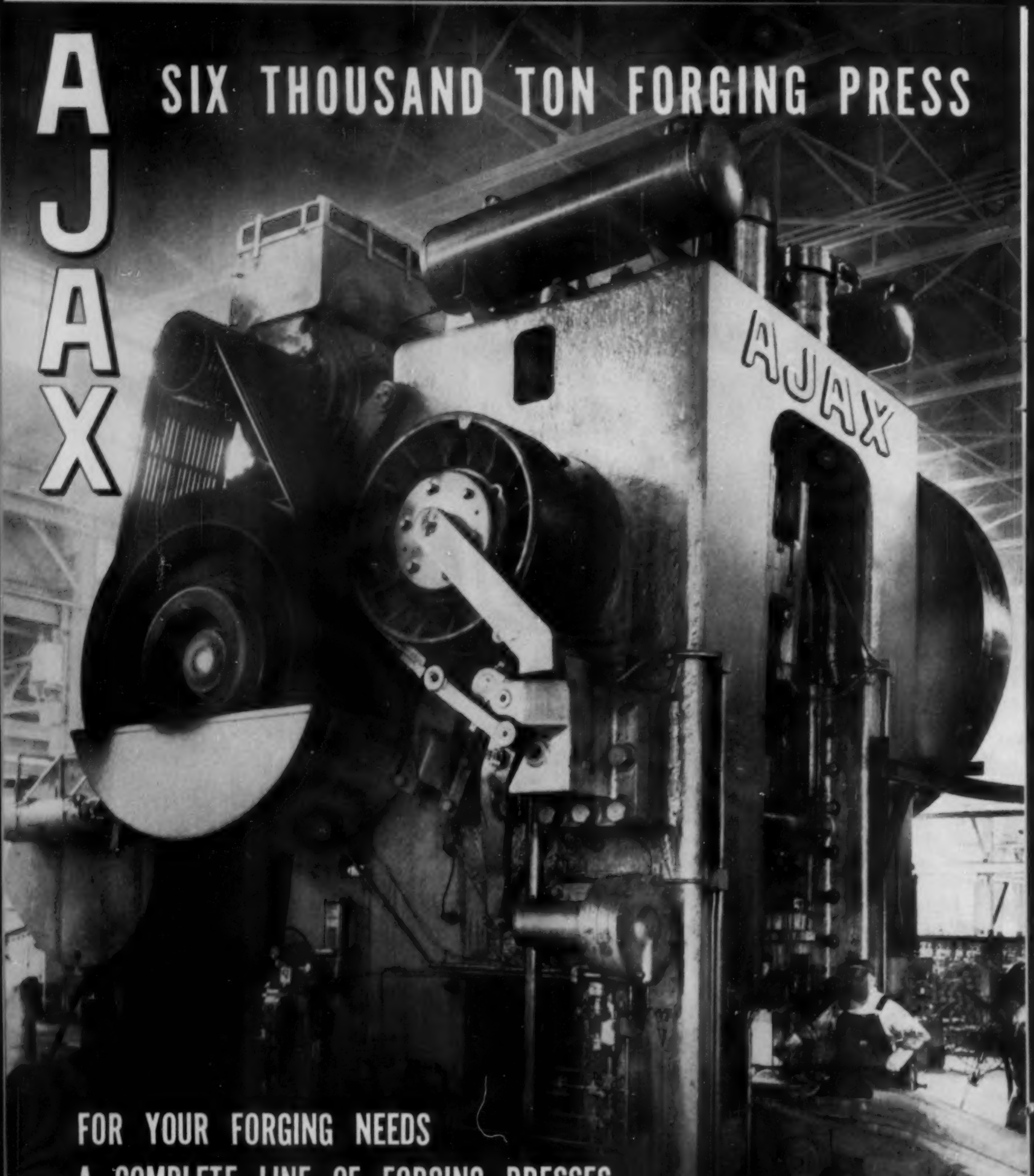

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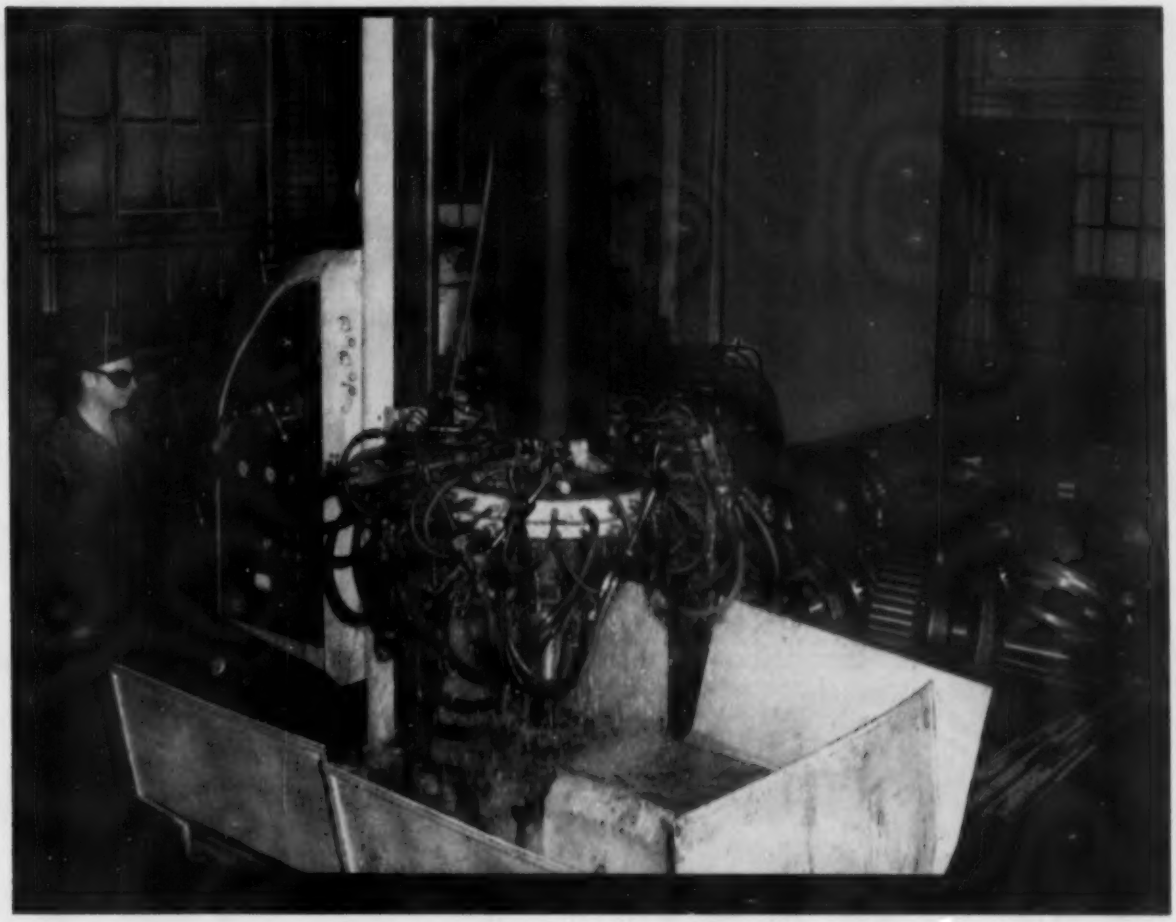

Flame hardening big mill roll at Lakeside through scientifically controlled multiple oxygen acetylene flames.

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THE *Lakeside Steel Improvement Co.*

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The Properties of Straits Tin

No other metal combines all the properties of Straits Tin. No other metal can do so many different kinds of jobs so economically and so well.

Because it is corrosion-resistant, nontoxic and tasteless, tin is a perfect metal for the packaging of food. Today more than 400 different food products come in tin cans. Currently, more than half of the tin for these cans is Straits Tin from Malaya.

Because it wets metals readily, flows easily, adheres firmly, and has a relatively low melting point (450°F.), tin is the key component of solder. And tin-rich solders are the best and most efficient means for making corrosion-resistant, impermeable, electrically conductive joints at low temperatures.

A unique combination of properties makes Straits Tin a particularly useful component of bronzes. Tin hardens and strengthens copper twice as effectively as zinc, and provides much better resistance to corrosion.

Because of its antifriction qualities, resistance to corrosion, conformability, and good embedding characteristics, tin is invaluable in bearing metals. Without tin-base or tin alloy bearings, the wheels of industry could not turn so smoothly and efficiently.

And Straits Tin is not only one of our most useful metals. It is now fast becoming one of our most valued chemicals. Tin in chemical compounds — stabilizers, opacifiers, antioxidants, preservatives — is contributing greatly in the competitive race for improvement in products from plastics and the new chlorinated rubber paints to ceramics, sensitized paper — now even jute bags.

Take a New Look at Straits Tin

Over one-third of the world's tin is mined and smelted in Malaya. Known as Straits Tin, this metal is over 99.87% pure, and is world-famous for its absolute reliability of grade.

Today new uses for Straits Tin are making it more valuable than ever to American industry. And continuing research will, in the near future, find still more ways in which Straits Tin can serve you. Whether you're planning a new product, improving an old one, or seeking ways to avoid the squeeze between rising costs and resistance to higher product prices, a careful reappraisal of the properties of Straits Tin may uncover a profitable answer to your problem.

MALAYAN
TIN
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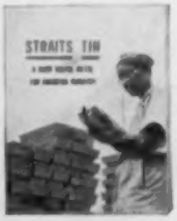
A new booklet, "Straits Tin: A Most Useful Metal for American Industry," tells a factual and intriguing story of the many new ways tin can be used today. A copy is yours for the asking.



THE MALAYAN TIN BUREAU

Dept. 25, 1028 Connecticut Ave., Washington 6, D.C.

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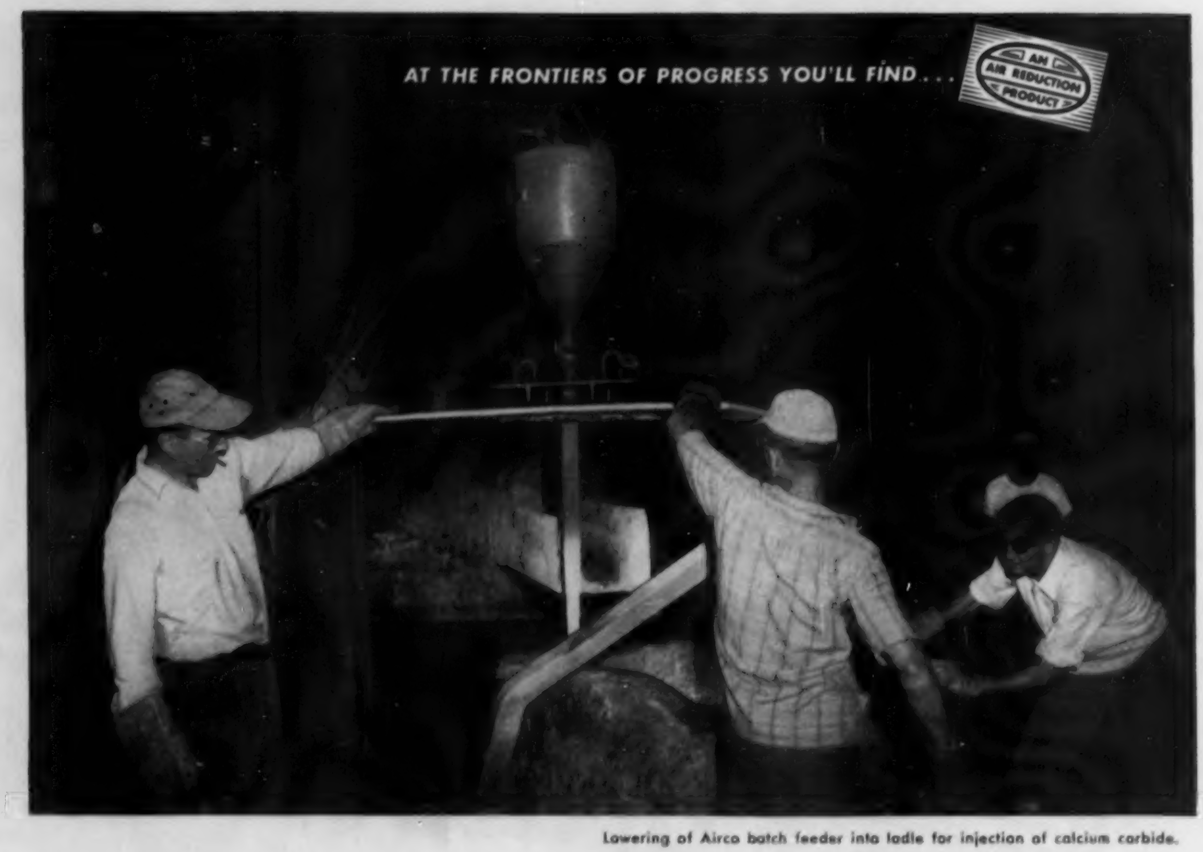
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AN AIR REDUCTION PRODUCT

Lowering of Airco batch feeder into ladle for injection of calcium carbide.

Now! Gray-Iron foundries can reduce cost of producing ductile iron

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The new calcium carbide injection process is the result of Airco Technical Service's continuing effort to find new, profitable techniques for customers. If you have a cutting, welding or metallurgical problem, why not ask Airco to help you? Write to your nearest Airco office.

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MIRROCU copper bright dip. LUSTRABRASS brass bright dip. M-601 burnishing compound. DB Electrolytic Strip for electrodeposits. Paint Strippers. Etch Salts for acid dipping leaded brass. METEX A-82 dip to prevent staining. Cleaning Compounds for all cycles.

ZINC BASE DIECASTINGS

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ALUMETEX Process for plating on aluminum. MACDERMID ALUMINUM BRIGHT DIP. METEX #79 liquid burnishing compound. Pickling Aids for silicon alloys. DEOXIDEX Process preparation for spot welding. NON-ETCH anodize strippers. METEX SS STRIPPER for removing copper, nickel and cadmium. Paint Strippers. Cleaning compounds for all processing.

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Use this fast, safe Hooker Process for descaling steel and titanium

Descale alloy steels and titanium in any form—rapidly, safely—using the Hooker Process with Virgo® Descaling Salt.

A bath of molten Virgo Descaling Salt quickly converts scale, rust, and other surface impurities to an acid-soluble coating. A quench, acid dip, and final spraying then remove this coating in from one-tenth to one-hundredth the usual pickling time, with no measurable effect on the base metal.

You can easily set up the Hooker Process for batch or continuous operation on any form of work including strip, sheets, bars, wire, tubes, plate, castings, forgings, and fabricated parts. You can usually process work as fast as your handling methods allow, with a minimum of supervision. Operation is safe for personnel, and there is little or no spent-acid disposal problem.

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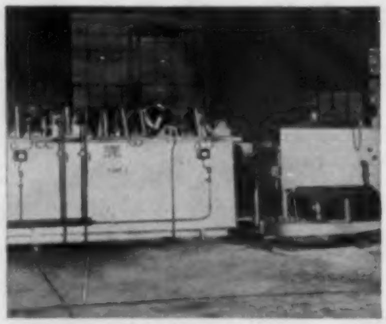
You'll get quick service on any descaling problem, by writing or phoning us. Complete test and engineering facilities are at your disposal, without obligation.

10-MINUTE IMMERSION loosens scale on 5 tons of stainless wire. A water quench, 3-minute acid dip, and final water rinse produce a clean, bright surface with no pitting or etching.



LIGHT-GAUGE ALLOY STRIP is descaled at 20-35 ft. per min. in this Virgo bath, after annealing.

Send for these bulletins—Get the whole story on Virgo Descaling Salt for alloy steels and titanium . . . how the Hooker Process works, its advantages, how to set up a Virgo descaling line, and the services you enjoy as a user. No obligation. Write us today.

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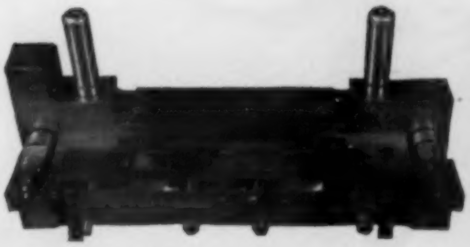

▲ Made from Bethlehem 67 Chisel, this die blanks ends for expanded steel joists. It turns out about 14,000 I-beam sections, varying in thickness from $\frac{3}{16}$ in. to $\frac{3}{8}$ in., before redressing is required. 67 Chisel is our popular chrome-tungsten shock-resisting steel.

Die of A-H5, used in cold-blanking sheet steel to produce ▶ differential housings for trucks and automobiles. Because A-H5 is an air-hardening steel, it has minimum size change in heat-treatment. It has 5 pct chromium, with 1 pct carbon. It resists wear and has good machinability.

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Whether you're looking for shock-resistance, wear-resistance, minimum distortion in heat-treatment, or some other characteristic, you'll find that your distributor has a grade of Bethlehem Tool Steel that you can count on to meet your needs.

When you use Bethlehem Tool Steel, you can select from more than forty individual types of steels included in our Carbon and Carbon-Vanadium, Oil- and Air-Hardening, Shock-Resisting, Hot-Work, High-Speed and Special-Purpose grades. It's well to remember, too, that if in doubt as to the proper heat-treatment for any grade of Bethlehem Tool Steel, the experience of our metallurgical staff is yours for the asking.

Wear-resistance and resistance to heat-checking and erosion in the extrusion of aluminum were the chief reasons for making this die of Cr-Mo-W (Chrome-Moly-Tungsten). Cr-Mo-W, a general-purpose hot-work tool steel, has a 5 pct chromium content.

Alloy bars being inspected at a Bethlehem mill.

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If you have a problem relating to alloy steels, their selection or treatment, the experience of Bethlehem metallurgists is at your service. Our staff will gladly help you select the proper alloy steels, and is prepared to give unbiased advice on analyses, heat-treatment, machinability, and expected results. Please feel free to call upon us at any time.

BETHLEHEM STEEL COMPANY, BETHLEHEM, PA.
On the Pacific Coast Bethlehem products are sold by Bethlehem Pacific Coast Steel Corporation. Export Distributor: Bethlehem Steel Export Corporation

BETHLEHEM STEEL

BETHLEHEM STEEL

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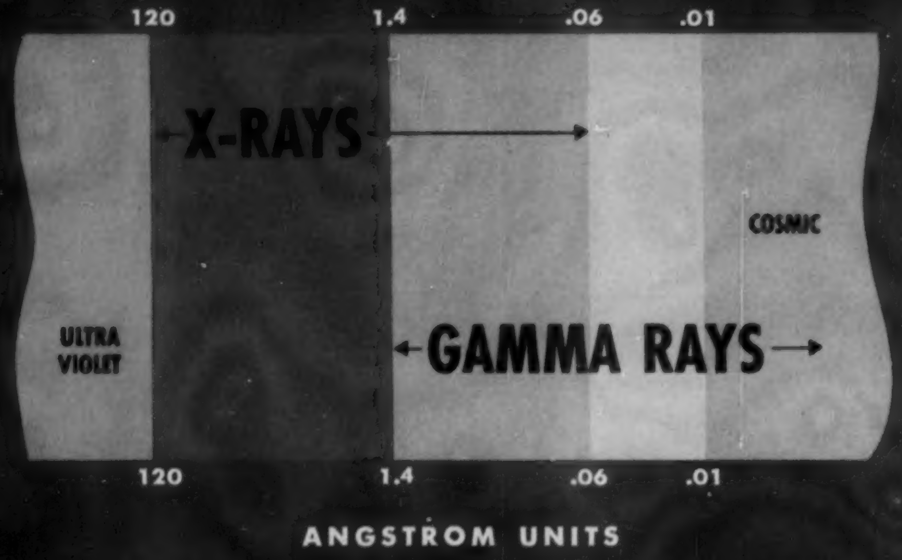

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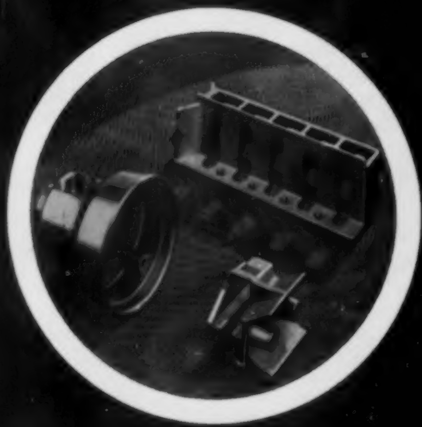

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One of Titan's modern automatic chucking machines for preparing brass and aluminum forgings to customer specifications. Titan performs all types of machining operations.

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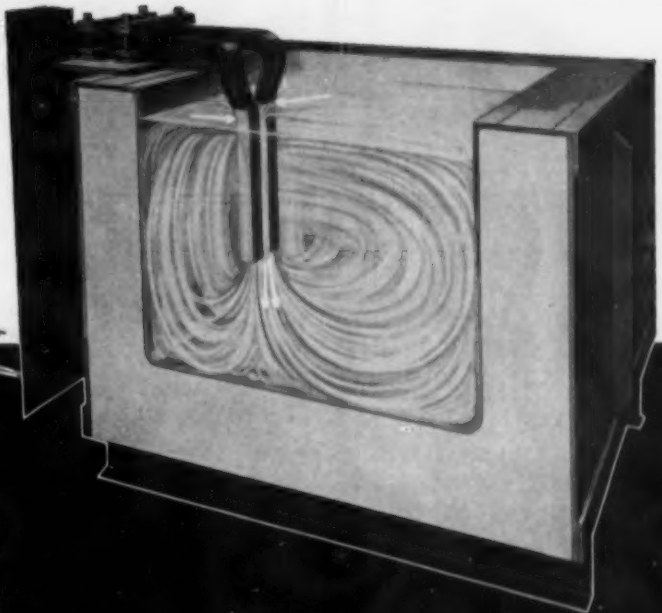

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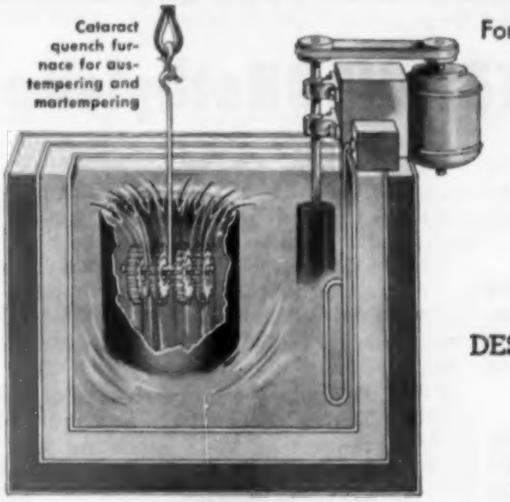
Salt Bath Furnaces



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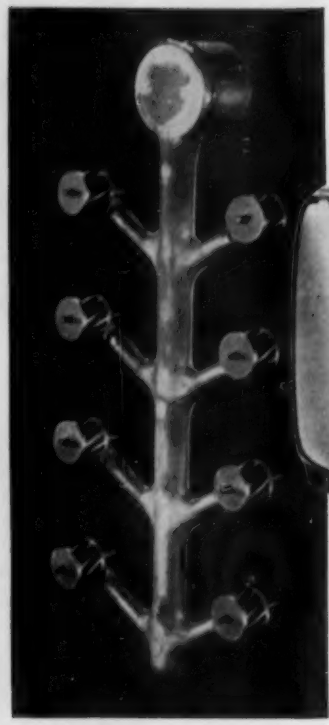

Over 600 of these rotor gates are die cast each day, thus producing over 4800 of the finely detailed rotors shown above in two-thirds actual size.

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depends on an electric motor …so

Toastmaster chose Kux die casting machines

to make the heart of the motor…

a tiny aluminum rotor

The Toastmaster Products Division of McGraw Electric Company has a recipe for perfect toast with its new Super Deluxe Toaster. Merely place the bread in the toaster . . . it lowers the bread, starts it toasting and serves it up fast . . . all by itself!

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FOREWORD

THIS is the Second Supplement to the 1948 edition of the Metals Handbook. Like the 1954 Supplement, this volume is intended to increase the usefulness of the Handbook by bringing up to date the information on specific subjects in which scientific and technological progress has been great, and by introducing new subjects of current interest.

Following publication of the First Supplement, the Metals Handbook Committee made a further selection of subjects important for the next complete Handbook and appointed 19 author committees to deal with the selected topics. As in 1954 the committees' contributions are presented first in a Supplement, rather than being held until the entire revised Handbook is completed.

It has been by the faithful work and cooperation of the members and others that the Society has been able to produce the Metals Handbook and its Supplements. The Board of Trustees wishes to express its sincere appreciation to all the committeemen and members of the American Society for Metals who have contributed so generously in assembling the information contained in the reports of the various committees.

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The Selection of Sheet Steel for Formability

By the ASM Committee on Formability of Sheet Steel

THIS ARTICLE deals with the selection of both cold rolled and hot rolled low-carbon sheet steels of the types and qualities used for stampings.

Selection is discussed from the point of view of the measurable formability required to make parts of specific forming severity. Mechanical properties are correlated with formability, and the percentage stretch of the metal in the die is the measure of forming severity. Also discussed from the viewpoint of their effect on formability are surface finish of the sheet, directionality, grain size and aging, together with processing effects such as speed of forming, sheared edges, lubrication and tooling.

Severity Classification

Even in normal times it is difficult to select the most economical class of steel for individual parts with requirements that may vary from mild bending to severe drawing. In times of steel shortage the problem is overwhelming. Selection can be greatly simplified, however, by using a system of severity classification to correlate the severity of the forming operation with the mechanical properties of the steel. The benefits to be derived from the severity classification are these: more accurate estimates of cost can be made in advance because choice of the proper steel is assured; quality of incoming steel can be controlled more closely; and rejected or substandard steels may be reclassified and allocated to other parts of less severity on a definite basis.

By use of the severity classification system* shown in Table I, any of seven forming severities can be associated with definite mechanical properties of one of the five classes of cold rolled steels used for formed parts. For hot rolled steels, Table II is used similarly to select properties for one of the four corresponding classes of forming severity.

The best way to build the file of data and experience necessary for quick and accurate classification of new parts is first to classify existing production parts. Severities of class 1 and class 2 are easily identified visually. Severities of classes 3 to 6K inclusive require a correlation of the performance with mechanical properties of steel in sufficient variety to establish limits, or a measurement of the stretch in the critical areas, as described in later paragraphs.

Subdivisions

Severity Classification **1**
Examples of Selection **2**
Selection of Test Specimen .. **3**
Olsen Cup Test **3**
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Lubrication **11**
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Allowable Reduction of Drawn Cups **11**

ASM-SLA Q23, G4, ST

In the bidding stage on new parts, the *estimated severity classification* of the part should be arrived at by comparison with similar parts of known severity. Later, when the die drawing or a plaster cast of the die is available, a more accurate *tentative severity classification* should be made by comparing the actual shape with that of similar parts, so that the first order for steel can be placed.

This is a new subject for the ASM Metals Handbook

In 5 to 10% of all selections of steel for the initial order, the severity of the part will prove deceptive. Therefore, classification at the first two stages should be liberal. For example, if there is some question whether a stamping is of class 3 or class 4 severity, it should be rated as severity 4 and the corresponding steel chosen from Table I or II.

Establishing the *final severity rating* of classes 3 to 6K inclusive requires a measurement of stretch in the critical areas or, better still, a correlation of performance with mechanical properties. When performance is correlated with properties, average and below-average steel (Fig. 1) of successively poorer classes should be tried until material is found that gives unsatisfactory performance. Then the poorest class that will just meet requirements can be identified.

Whenever scrap loss because of forming difficulties is from 1 to 2%, the steel has been selected correctly and, using Table I or II, its properties determine the severity of the part. Conversely, if severity is known, the properties of the metal can be determined from the table.

When there is little or no scrap loss because of forming difficulties, a lower class of steel may often be substituted at a saving. When a scrap loss of 1 to 2% indicates correct selection, the percentage stretch of the metal during forming (as measured from a 1-in. square grid pattern scribed or rubber-stamped on the unformed blank, as shown in Fig. 2, will conform to the mechanical properties indicated in Table I or II in almost every instance. Measurements of stretch taken over longer gage lengths will give lower average values, rather than the critical maximum value. Conversely, measurements of stretch made over lengths of ½ in. or less may give values considerably higher than those listed in Tables I and II.

---

*Developed originally by Paul G. Nelson of The Budd Co.

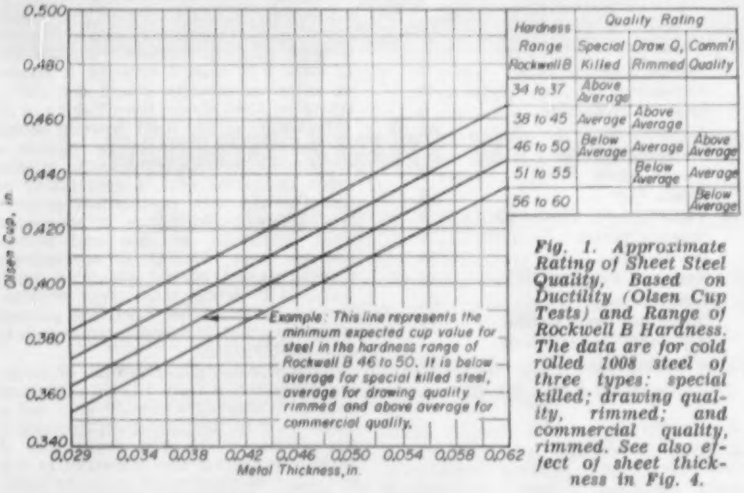
Table I. Severity Classification for Cold Rolled 1008 Steel Sheet Up to 0.062 In. Thick

Severity Class	Type of Forming Operation	Severity of Bend or Stretch[a]	Minimum Olsen Cup,[b] in.	Maximum Rockwell B Hardness	Class of Cold Rolled 1008 Steel Sheet[c] Exposed Part	Unexposed Part
1 (CR)	90-deg bend	1 t radius min	.....	80[d]	Commercial quality, rimmed and temper passed[e]	Commercial quality, rimmed, annealed[e]
2 (CR)	Up to 180-deg bend Drawing	0.01-in. radius min 10% max	..... 0.340	65	Commercial quality, rimmed and temper passed[f]	Commercial quality, rimmed, annealed[f]
3 (CR)	Drawing	10 to 20%	0.365	55	Commercial quality, rimmed and temper passed[g]	Commercial quality, rimmed, annealed
4 (CR)	Drawing	20 to 30%	0.385	50	Drawing quality, rimmed and temper passed	Commercial quality, rimmed, annealed[g]
5 R (CR)	Drawing	30 to 35%	0.390	45	Drawing quality, rimmed and temper passed[g]	Drawing quality, rimmed, annealed[g]
5 K (CR) ...	Drawing with possible buckling	30 to 35%	0.385	47[h]	Drawing quality, killed and temper passed	Drawing quality, killed and temper passed
6 K (CR) ...	Drawing with possible buckling	35 to 40%	0.400	42	Drawing quality, killed and temper passed[g]	Drawing quality, killed and temper passed[g]

(a) These values are based on the greatest percentage stretch of the metal as measured between lines which, before forming, are marked on the blank as a grid pattern of 1-in. squares. The values do not apply to stretch measured over either longer or shorter gage lengths. (b) Values shown are for 0.036-in. thickness. The corresponding values for other thicknesses may be read from the graph of Olsen cup values vs thickness (Fig. 4). (c) Exposed or "outside" parts must retain an acceptably smooth appearance after forming. In unexposed or "inside" parts, wrinkles, stretcher strains or other defects in appearance are permitted. (d) The acceptable value of hardness for 90-deg bends parallel with the direction of rolling is Rockwell B 70 max. (e) 1020 steel can also be used but 1008 or 1010 may cost less. (f) 1010 steel is also suitable. (g) Steels of the required mechanical properties are not available from all suppliers in all sections of the country. (h) The yield point and elastic ratio are more favorable than for severity 5 R (drawing quality, rimmed steel), as shown in Table III.

At the time of die tryout and during the first production run, stretch in critical areas should be measured and performance recorded in order to establish an accurate severity classification and thus enable the final selection of the lowest usable quality of steel. Further study and possible revision of the rating may be necessary later if gage, blank size, press speed or the die is changed.

The steels listed in Tables I and II will almost always make parts of the described severities. However, the mechanical properties listed are the governing factors, and cheaper steel with the required mechanical properties often can be purchased to make the part. The 1008 steel, preferred in all classes, is usually less expensive than 1020 and 1030, which appear in some instances in Tables I and II. These steels of higher carbon content are sometimes specified in stressed parts because of their higher yield point and tensile strength.



Hardness Range Rockwell B	Quality Rating: Special Killed	Draw Q, Rimmed	Comm'l Quality
34 to 37	Above Average		
38 to 45	Average	Above Average	
46 to 50	Below Average	Average	Above Average
51 to 55		Below Average	Average
56 to 60			Below Average

Fig. 1. Approximate Rating of Sheet Steel Quality, Based on Ductility (Olsen Cup Tests) and Range of Rockwell B Hardness. The data are for cold rolled 1008 steel of three types: special killed; drawing quality, rimmed; and commercial quality, rimmed. See also effect of sheet thickness in Fig. 4.

Examples of Selection

When the steel has been properly selected, any steel of *lower* mechanical properties will give a rejection or scrap rate that increases costs, and any steel of *higher* mechanical properties may increase cost directly through the higher price of the steel. Examples of proper selection, covering the seven severity classifications for cold rolled steel and the four severity classifications for hot rolled steel, are illustrated by the examples and accompanying data displayed on pages 3 to 11. In each illustration the percentage stretch is indicated, and the properties of the steel represent the minimum requirements to make the part in accordance with Tables I and II.

Complete results of the tests of each part should be recorded and filed in order to determine the minimum mechanical properties required to make the part and thus verify the severity rating. Such records may be summarized conveniently in graphical form as

Table II. Severity Classification for Hot Rolled Steel Sheet Up to 0.250 In. Thick

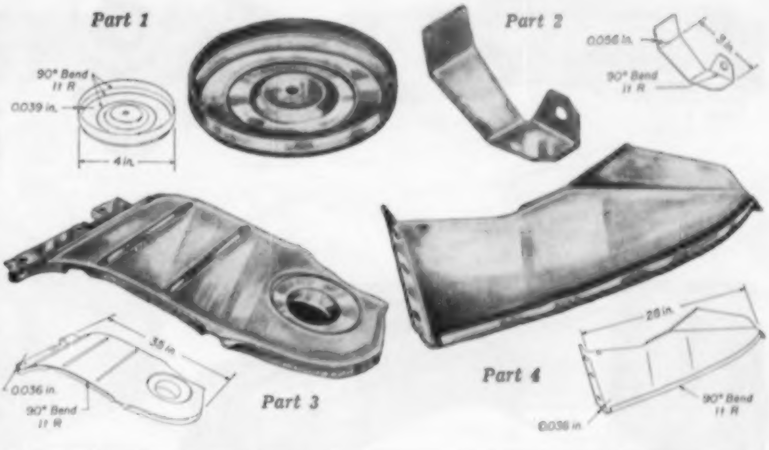
Severity Class	Type of Forming Operation	Severity of Bend[a] or Stretch[b]	Minimum Elongation in 2 In.,[c] %	Maximum Rockwell B Hardness	Class of Hot Rolled Rimmed Steel[d]
1 (HR).........................	90-deg bend	1 t radius min up to 0.090 in. thick 2 t radius min up to 0.250 in. thick	...	80	Commercial quality 1008 to 1030
2 (HR).........................	90-deg bend 180-deg bend Drawing	1½ t radius min up to 0.250 in. thick ¾ t radius min up to 0.090 in. thick 10% max	30	68	Commercial quality 1008 to 1015
3 (HR).........................	Drawing	10 to 20%	35	60	Commercial quality 1008
4 (HR).........................	Drawing	20 to 30%	40	55	Drawing quality 1008

(a) Bend radii given are for bend axis parallel with rolling direction. For bends transverse to rolling direction, see Table VI. (b) These values are based on the greatest percentage stretch of the metal as measured between lines which, before forming, are marked on the blank as a grid pattern of 1-in. squares. The above values do not apply to stretch measured over either longer or shorter gage lengths. (c) Values shown are for thickness of 0.090 in. Corresponding values for other thicknesses may be read from the curve for hot rolled steel in Fig. 4. (d) Commercial quality is normally rimmed but may be capped steel. Drawing quality is normally rimmed but may be capped, semi-killed or killed.

shown in the histograms of Fig. 3. These provide a statistical record of the properties of steel shipped by one supplier. The vertical lines labeled "min" and "max" indicate specified property limits originally thought necessary to make the part. Entries for properties of shipments that actually proved unsatisfactory for making the part are shown in double crosshatching. The part, shown at the top left of Fig. 3, was a cowl side made of drawing quality cold rolled steel, 0.034 in. thick. A maximum stretch of 28%, class 4 (CR) severity, occurred in the two bottom corners.

This form of presentation simplifies identification of the properties that cause steel failure in forming and emphasizes the comparison between inadequate properties and those specified. In addition, there is an indication of the range of properties to be expected in a series of shipments.

Stampings Typical of Severity Class 1(CR)



Part No.	Part Name	Exposed	Rockwell B Hardness	Olsen Cup, in.	Rimmed CR Steel Selected
1	Wheel half, toy	Yes	80 max	.....	CQ, tp
2	Bracket	No	80 max	.....	CQ, ann
3	Fender splash shield	No	80 max	.....	CQ, ann
4	Fender apron panel	No	80 max	.....	CQ, ann

Selection of Properties

The Rockwell hardness and the Olsen cup tests are usually the first, and frequently the only, formability tests made on either incoming steel or on steel that is causing an unacceptable number of rejected parts at the press. These tests are not always an exact measure of formability, but even in unusual instances they are approximately correct and therefore useful because they require a minimum of steel and of specimens for testing, and are made quickly on relatively inexpensive machines.

ASM Committee on Formability of Sheet Steel

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Technical Advisor to Works Manager
Heintz Mfg. Co.

When properly interpreted, the full data obtained from the tension test give an accurate and complete measure of formability — a measure considered inadequate at times, when actually maintenance of dies or equipment is at fault, or when samples are taken without regard to the nonuniformity in properties across the width of the sheet. One in about 10,000 stampings is entirely too severe to be made, and for such parts the slightest variation in steel quality or thickness, die finish, die bearing, die pressure or lubrication will cause breakage. The proper solution is not to improve formability tests or to select a more formable steel but to improve die design, change the shape of the part or increase the number of forming operations and reduce the severity of each.

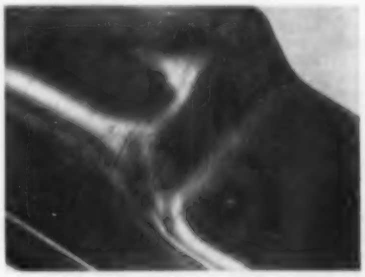


Fig. 2. Close-Up View of Oil Pan Showing Area of Greatest Stretch During Forming (32% in 1 In.). A grid of 1-in. squares inscribed on the unformed sheet served as a reference for measurements of stretch after forming.

Selection of the Test Specimen is as important as the test itself. The specimen should be representative of the sheet. In large coils the ends differ in properties from the body of the coil; therefore test specimens should be cut after uncoiling 50 to 100 ft, again near the center and again from the inside coil end. Hardness is usually less at the edges of both sheets and coils than at central locations, particularly in rimmed steel. Furthermore, the severest stretch in a stamping takes place well in from the edge, so the test specimens should be taken from the central three fourths of the width.

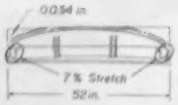
Specimens for cup tests should be long enough to make two tests or more at least 12 in. apart across the width of the sheet or coil. For tension tests, one or two specimens should be cut parallel to, and another perpendicular to, the direction of rolling. When tests and performance do not correlate, hardness and cup tests should be made at frequent intervals across the sheet, particularly in the area in line with the breakage, to check the uniformity of properties. Also, tension tests should be made in the area of breakage.

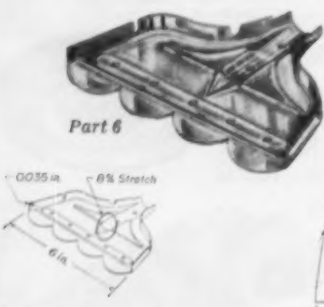
The Olsen Cup Test is made on a sheet specimen 3⅝ in. wide held between flat ring dies of 1-in. inside diam. A ball of ⅞-in. diam is pushed progressively against the sheet to form a cup while the punch load and height of cup are indicated continuously. The Olsen cup value recorded is the height of the cup in thousandths of an inch at the instant the punch load starts to drop suddenly. Load values are not otherwise significant. Some laboratories read the cup height at visible fracture, which results in cup values higher by 0.010 to 0.020 in. and presents greater difficulty in duplicating results. Sheet thicknesses for the standard Olsen cup test are limited to 0.062 in., because of the clearance between the ball and ring. Tests on thicker sheet, using larger ring dies, seem to be an unreliable measure of formability. The cup height is a fair measure of relative formability of different sheet thicknesses when corrected for thickness according to Fig. 4. The variation of cup height with both thickness and metal quality is also shown in Fig. 1.

Those experienced in using this test can predict the approximate coarsening behavior of the steel after forming, by examination of the sides of the cup. With grain size of ASTM 8 to 9 the sides are smooth. With grain size 7 there is moderately heavy roughening, which becomes progressively coarser as grain size increases. Mild directionality of the sheet is predictable on the basis of nonuniform necking down around

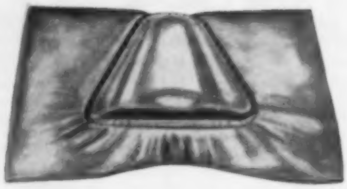
Stampings Typical of Severity Class 2(CR)

Part 5

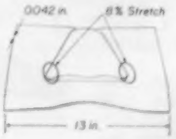




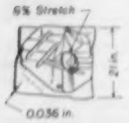
Part 6

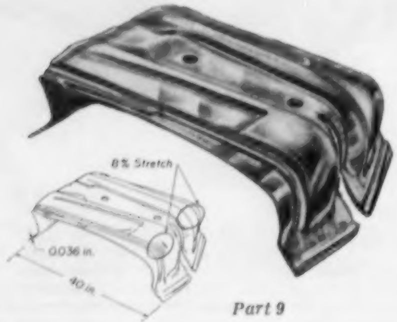


Part 7

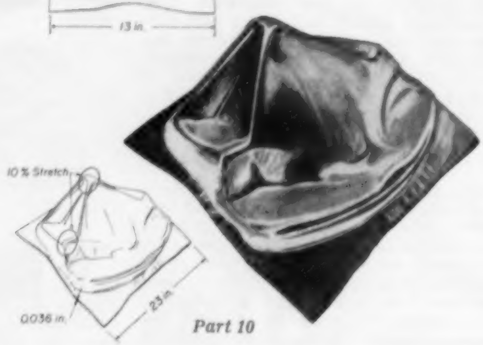


Part 8





Part 9



Part 10

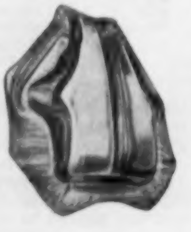
Part No.	Part Name	Exposed	Rockwell B Hardness	Olsen Cup, in.	Rimmed Cold Rolled Steel Selected
5	Shelf panel	No	65 max	0.335 min	Commercial quality, annealed
6	Broom plate	Yes	65 max	0.337 min	Commercial quality, temper passed
7	Stone deflector end	Yes	68 max	0.355 min	Commercial quality, temper passed
8	Engine shield	No	65 max	0.340 min	Commercial quality, annealed
9	Front seat side shield	Yes	65 max	0.340 min	Commercial quality, temper passed
10	Quarter panel filler	No	65 max	0.340 min	Commercial quality, annealed

the periphery of the fracture zone. Stretcher strain marking in the flat portion immediately adjacent to the cup means that the steel may flute or form stretcher strains when drawn.

Rockwell B Hardness readings are reliable on sheet as thin as 0.030 in., but below this the Rockwell F scale should be used to avoid error because of the anvil. Hardness correlates fairly well with tensile strength but is also affected by the yield strength. In addition, hardness is one of the indications of the spring back that may be expected on an operation. A 10-point hardness range is usually satisfactory to meet ordinary tolerances.

Tension Test specimens should be made according to the ASTM standard specimen shown in Fig. 2 on page 87 of the 1948 Metals Handbook. Some fabricators blank out the test specimens with a die and finish the edges within the gage length by draw filing. The speed of testing should be constant at about ¼ to ½ ipm. It is desirable to use autographic equipment that draws a complete diagram of load versus extension with the strain magnified 10 to 1 and with the load coordinate at least 8 in. high. Otherwise, a low-magnification strain gage may be used to determine the yield point elongation, uniform elongation and the yield point when the load-extension diagram is smooth.

The determination of yield point is complicated by the variety of load-extension contours, which depend on the condition of the steel. In steels with a drop-in-load and a horizontal portion, or with a horizontal portion only, the yield point is taken as the



This cowl side is shown as Part 21 in the group of stampings typical of severity class 4 (CR) on page 6. Maximum stretch, 28%, is at the bottom corners. See distribution of steel properties in Fig. 3 below.

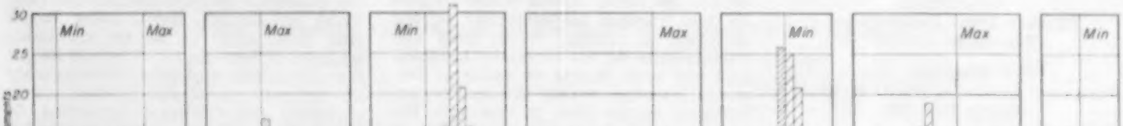
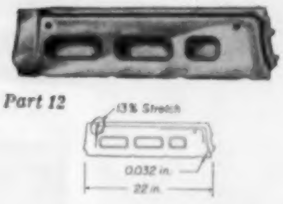
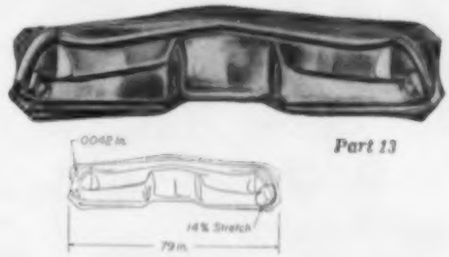


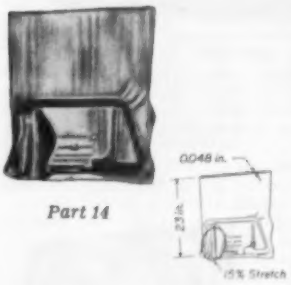
Fig. 3. Distribution of Properties of Steel from Various Shipments Supplied by a Single Mill, and Acceptability for Making the Part Shown at Left Above the Histograms. Vertical lines labeled "Min" and "Max" indicate specified property limits originally thought necessary to make the part. Entries for properties of shipments that actually proved unsatisfactory for making the part are shown in double crosshatching. The entries more closely crosshatched in one direction indicate shipments that made the part satisfactorily although falling outside the original specification limits.

Stampings Typical of Severity Class 3(CR)

Part 11
12% Stretch
0.048 in.
24 in.


Part 12


Part 13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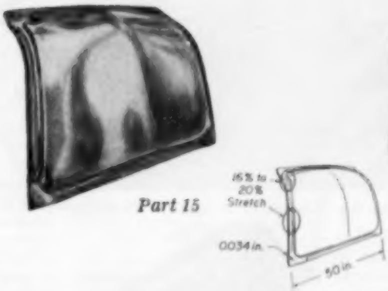
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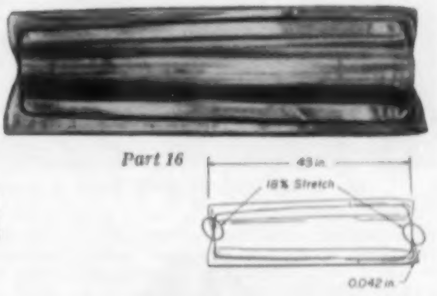

Part 16

Part No.	Part Name	Exposed	Rockwell B Hardness	Olsen Cup, in.	Rimmed Cold Rolled Steel Selected
11	Reinforcement	No	55 max	0.395 min	Commercial quality, annealed
12	Lock pillar	No	55 max	0.355 min	Commercial quality, annealed
13	Stone deflector	Yes	55 max	0.380 min	Commercial quality, temper passed
14	Truck corner reinforcement	No	55 max	0.395 min	Commercial quality, annealed
15	Outer deck lid	Yes	55 max	0.360 min	Commercial quality, temper passed
16	Tractor hood top	Yes	55 max	0.380 min	Commercial quality, temper passed

average stress in the horizontal portion, as shown in *(a)* and *(b)* of Fig. 5. In steels with a jog in the curve, the yield point is the stress at the bottom of the jog, as in *(c)* of Fig. 5. In steels with a smooth curve, the yield point is chosen arbitrarily as the stress at 0.5% extension under load, as in *(d)* of Fig. 5.

Tensile Strength is important in formability; and the higher it is, the better, if other properties are favorable.

Yield Point is very significant and is best at its lowest value if other properties are favorable. For example, low yield point resulting from exceptionally large grain size is undesirable, since the surface will become very rough (because of "orange peel") after forming, and the elongation and tensile strength will be too low. Steel low in yield point deforms easily in compression, so there is less tendency for buckles to form or to remain.

Upper Yield Point is often reported when the steel exhibits a drop in load at the yield point. The value obtained is very sensitive to specimen alignment. This property has no significance except to indicate the tendency of the steel to form stretcher strains.

Elastic Ratio (the yield point divided by the tensile strength) is important for any type of severe stretching. The lower this value, the greater the spread between yield strength and tensile strength, and the more suitable the steel for severe forming. In steel with a low elastic ratio the stretching is more evenly distributed between moderately and highly stressed areas of the stamping, rather than being concentrated at only the highly stressed areas.

Elongation is a direct measure of ductility in stretching, and therefore, if other properties are favorable, the steel with the highest elongation is the most formable. Elongation increases with increasing thickness of sheet in the manner shown in Fig. 4. The actual values are those desired for drawing quality steel, either rimmed or killed. As might be expected, increasing the thickness of sheet adds slightly to the average expected formability of the steel. However, adding thickness is a very costly way to gain formability.

Uniform Elongation is correlated closely and directly with the amount of deformation that can occur before localized necking, beyond which forming operations are undesirable or unsafe. It is measured on the load-extension diagram to the point at which the load falls rapidly from a maximum to final rupture. (This is shown in Fig. 1 on page 106, 1948 Metals Handbook.)

Yield Point Elongation is the percentage of elongation that occurs during

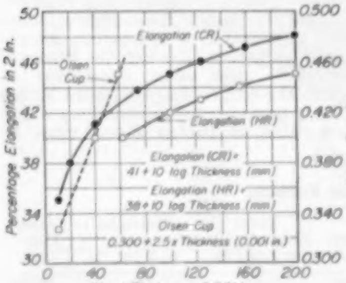


Fig. 4. Effect of Thickness on Elongation and Olsen Cup Values. Data shown are those desired for sheet of drawing quality, either rimmed or killed, with separate curves for cold rolled and hot rolled steel.

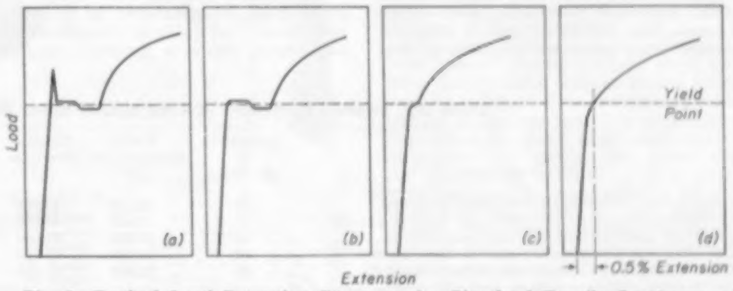
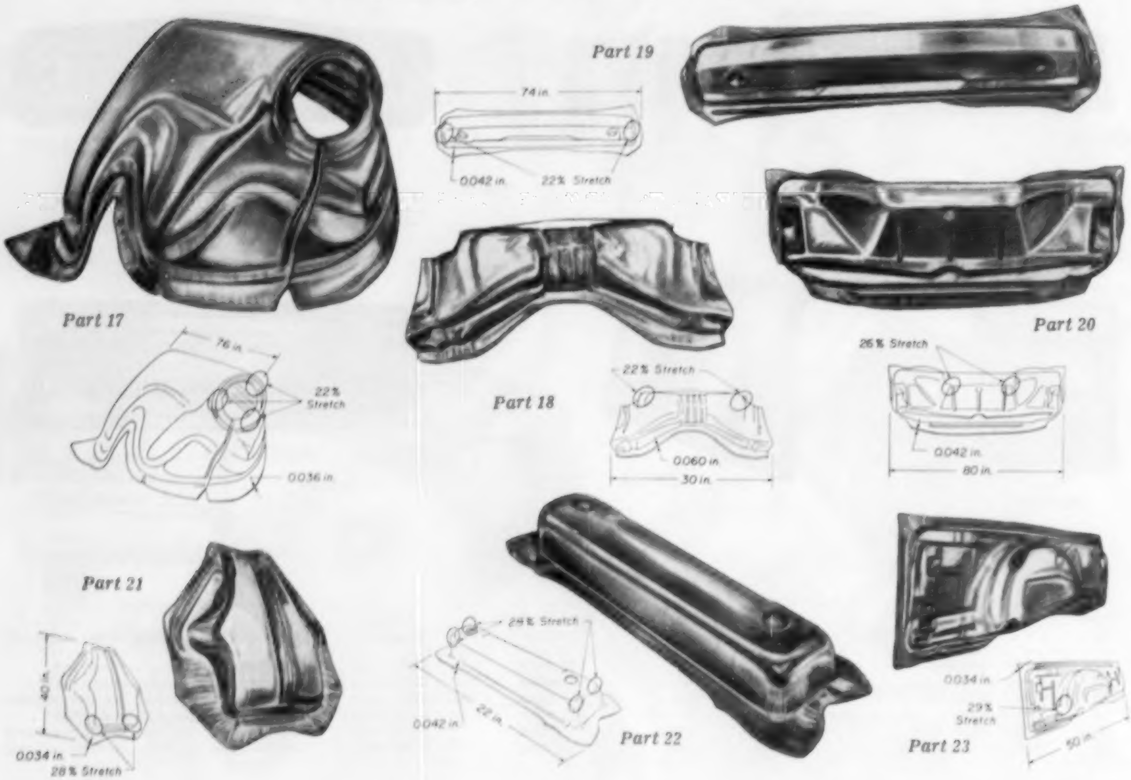


Fig. 5. Typical Load-Extension Diagrams for Standard Tensile Specimens of Low-Carbon Sheet Steel. See text for discussion of the four types of curves.

Stampings Typical of Severity Class 4(CR)



Part No.	Part Name	Exposed	Rockwell B Hardness	Olsen Cup, In.	Rimmed Cold Rolled Steel Selected
17	Front fender	Yes	50 max	0.385 min	Drawing quality, temper passed
18	Hood hinge bracket	No	50 max	0.445 min	Commercial quality, annealed
19	Truck radiator grill	Yes	50 max	0.400 min	Drawing quality, temper passed
20	Radiator support	No	50 max	0.400 min	Commercial quality, annealed
21	Cowl side	Yes	48 max	0.390 min	Drawing quality, temper passed
22	Valve cover	Yes	50 max	0.400 min	Drawing quality, temper passed
23	Wheelhouse	No	50 max	0.380 min	Drawing quality, annealed

yielding in steel that exhibits a sharp yield point. It is a direct measure of the depth or intensity of stretcher strains that will develop in lightly formed areas. Even a small yield point elongation is therefore undesirable in exposed parts, and must be eliminated by roller leveling with a break roll in order to obtain a satisfactory surface finish. Yield point elongation is of slight significance in formability.

Desired Properties are mechanical properties necessary in a class of steel to insure efficient pressroom production. They represent reasonably good values chosen from the range usually supplied, rather than premium qualities at premium prices. The desired mechanical properties of classes of steel ordered to quality standards are given in Table III. This table, with particular reference to sheet thickness of 0.036 in., covers cold rolled steel used for a variety of formed parts. In addition, the ranges of Olsen cup and Rockwell B hardness are given in Fig. 1 for above-average, average, and below-average quality of cold rolled steel in special killed, drawing quality and commercial quality classes of various thicknesses.

Direction of Rolling. The ductility of sheet steel, as measured by the total elongation, the uniform elongation and the elastic ratio, is generally slightly better in the direction of rolling than in the transverse direction. Therefore, whenever it is feasible from the standpoint of cost, blanks for stampings should be laid out so the critical stretch is parallel to the direction of rolling.

Killed Steel

As defined in the AISI Steel Products Manual on Carbon Steel Sheets, killed steel is generally a low-carbon aluminum-killed steel, although the producer sometimes uses other deoxidizers to obtain the proper characteristics. Killed steel is intended for applications where cold rolled or coated sheets must be

Table III. Desired Properties of Cold Rolled Sheet Steel for Forming

Class of Steel	Rockwell B Hardness	Yield Strength,(a) psi	Tensile Strength, psi	Elastic Ratio	Total Elongation(b) in 2 In., %	Uniform Elongation(b) in 2 In., %	Olsen Cup,(b) in.
Commercial quality, rimmed and annealed	50	35,000	42,000	0.85	37	23	0.380
Commercial quality, rimmed and temper passed	55	35,000	44,000	0.80	35	19	0.370
Drawing quality, rimmed and annealed	45	32,000	41,000	0.75	41	25	0.400
Drawing quality, rimmed and temper passed	48	30,000	42,000	0.70	39	23	0.390
Drawing quality, killed and temper passed	45	25,000	41,000	0.60	41	26	0.400

(a) The yield strength given is in the rolling direction. The value in the transverse direction is 2000 psi higher. (b) The values given are for 0.036-in. thickness. For corresponding values of elongation and Olsen cup of other thicknesses, see Fig. 4.

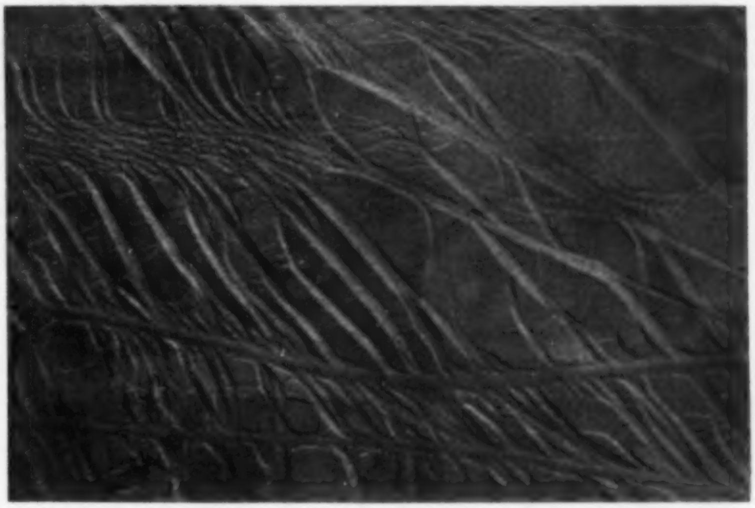


Fig. 6. Stretcher Strains in a Sheet Steel Part. ¾ actual size

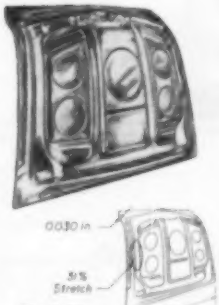
free from significant changes in mechanical properties (strain aging) for a long time; where stretcher strains without roller leveling are not permitted; or where better mechanical properties are desired for operations too severe for rimmed steel of drawing quality. It is a steel of premium price.

Generally, killed steel has mechanical properties superior to rimmed steel of drawing quality (particularly, it has low yield point and elastic ratio) and has better formability and performance, less tendency to form buckles, and is usually free from aging. However, inferior surface properties and more surface defects can be expected from killed steel than from rimmed steel, with consequent higher scrap or repair loss because of these defects, although surface defects have decreased greatly during the past year. Also, panels produced from aluminum-killed steel are usually less resistant to handling damage and "oil can", because of the lower yield strength of this steel.

Most major producers of stampings restrict the use of aluminum-killed steel to the most severe draws, to low-volume parts when the steel inventory cannot be used before aging begins in rimmed steel, and to small or irregularly shaped parts for which sheet cannot be roller leveled successfully.

Specifying killed steel is not necessarily an assurance that all sources of difficulty will be removed. Killed steel can be produced improperly with resultant stretcher strains, undesirable equi-axed grain structure, surface slivers and a tendency to strain age. If it has strain aged, stretcher strains will be present and it may be impossible to remove them by roller leveling.

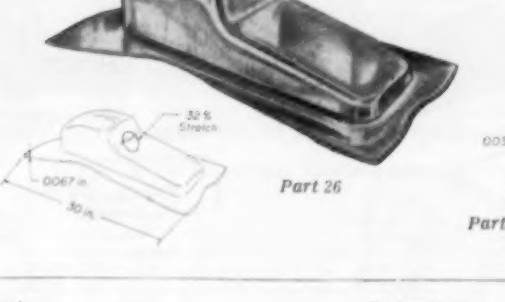
Stampings Typical of Severity Class 5 R(CR)



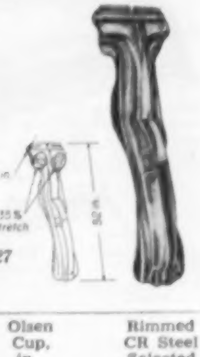
Part 24

0.042 in
32% Stretch
73 in

Part 25



Part 26



Part 27

Part No.	Part Name	Exposed	Rockwell B Hardness	Olsen Cup, in.	Rimmed CR Steel Selected
24	Inner deck lid............	No	45 max	0.375 min	DQ, ann
25	Truck fender	Yes	45 max	0.405 min	DQ, tp
26	Oil pan	No	45 max	0.460 min	DQ, ann
27	Center pillar	Yes	45 max	0.380 min	DQ, tp

To assure optimum performance, killed steel should have a fine, flat, elongated grain; ASTM grain size 7 to 8 is preferred. Stretcher strains may often be removed by roller leveling if the size and shape of the blank permit. However, this is the responsibility of the supplier, since one of the properties expected is usability without roller leveling.

Stretcher Strains

Stretcher strains, Lüders lines, the Piobert effect or (in shop parlance) "worms" are all characteristic markings that appear on the surface of low-carbon steel that has been annealed as a final mill operation (Fig. 6). These lines appear during the early stages of stretching and nearly disappear as the stretch exceeds 5 to 10%. In tension the lines are depressions in the surface, in compression they are raised, and in bending the same phenomenon causes flutes or kinks. Stretcher strains have no harmful effect on strength. In stampings that are exposed in service, stretcher strains are generally unacceptable because they show clearly through the paint.

Stretcher strains can be eliminated by a temper pass of about 1% cold reduction after the final anneal. Elimination is normally permanent in killed steel, but in rimmed steel, stretcher strains are almost certain to return objectionably in one week or less, depending somewhat on the amount of temper pass, the temperature, variables such as high nitrogen because of steelmaking practice, and the amount of forming in the stamping.

Stretcher strains can be eliminated from temper-passed rimmed steel and from insufficiently temper-passed killed steel by roller leveling through a Budd-McKay or United-Voss type of machine that flexes the sheet in bending enough to remove the sharp yield point and the yield point elongation that cause stretcher strains. This amount of cold work has no effect on the drawing quality. The sheets should be passed through the roller leveler once in each direction, because about 18 in. on the entering end of the sheet is not flexed. The stretcher strains usually return again by aging unless the steel is used within 24 to 72 hr.

Occasionally a lift or even a shipment of steel does not respond to roller leveling. If such material is unsatisfactory after two passes through the roller leveler, it should be rejected for use on exposed parts.

The performance of annealed steel used for a very difficult unexposed part may be improved by a single pass through the roller leveler, which will lower the yield point considerably by removing the bump in the load-extension diagram, and therefore will improve the elastic ratio.

Annealed sheet cannot be roller leveled for an exposed part because the flex roll kinks the sheet so severely that, after forming, the deformation will not disappear and, in addition, small stretcher strains will remain between the kinks.

Coil breaks and stickers have the appearance of stretcher strains, but coil breaks are regularly spaced and stickers are spotty. Roller leveling has no effect on these defects.

Strain Aging

The effect of aging of rimmed steel on formability is variable and may be unpredictable on the basis of tests. One rimmed steel may not age at all, while another may make the most difficult draws when received, and, after aging in storage for 30 days, may not make minimum draws.

During periods when quantity rather than quality is the chief factor in steel deliveries, breakage of rimmed steel in forming may be quite prevalent and is often attributed to aging, by the supplier. However, aging is less frequently blamed when steel is in good supply. Production records of several fabricators indicate conclusively that, depending on the supplier, aging effects in rimmed steel may or may not be perceptible in performance 60 days after delivery. Typical effects of aging on steel performance are presented in Fig. 7.

After an operation such as blanking, forming or finishing, strain aging is more pronounced than for unworked steel. It is therefore advisable to complete the sequence of operations on a part without intervening storage unless artificial aging tests indicate absence of aging.

Artificial aging tests give an approximate measure of the strain aging characteristics of the steel but do not predict the time at which definite changes in mechanical properties will occur. Artificial aging does not change the tensile strength appreciably, but yield strength and hardness will always increase while the elongation, uniform elongation and Olsen cup height will always decrease. Table IV gives typical results of laboratory tests made on 1008 steel 0.035 in. thick and of doubtful drawing quality. The results show that this particular steel exhibited maximum changes in properties after 70 days of natural aging; then the direction of change of some of the properties was reversed. For further information on strain aging, the reader may refer to the article, "Aging of Iron and Steel", page 438 of the 1948 Metals Handbook.

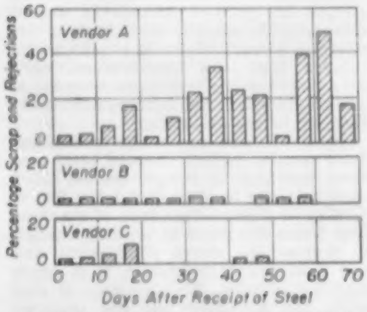


Fig. 7. Production Differences Caused by Aging of Sheet Steel. Metal performance values (expressed as total percentage scrap and rejections) are for identical parts made under the same production conditions.

Table IV. Changes in Properties of a Fast-Aging Cold Rolled 1008 Rimmed Steel

Aging Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 In., %	Rockwell B Hardness Number	Olsen Cup, in.
As Received	49.6 to 50.4	36.1 to 38.5	34.5 to 35.5	50 to 52	0.405
Natural Aging					
21 days at 73 F.........	49.9 to 51.0	37.5 to 40.3	33.5 to 34.5	53 to 54	0.400
70 days at 73 F.........	52.1 to 52.8	41.1 to 44.0	32.0 to 33.0	55 to 56	0.395 to 0.400
139 days at 73 F.........	51.8 to 52.1	40.6 to 42.9	32.5 to 33.0	56 to 57	0.395 to 0.405
173 days at 73 F.........	47.2 to 50.5	34.4 to 40.8	31.5 to 33.0	49 to 55	0.425
Artificial Aging					
1 hr at 212 F............	49.4 to 50.9	39.9 to 43.2	33.0 to 33.5	52 to 54	0.395
1 hr at 450 F............	50.8 to 51.6	43.3 to 45.5	31.0 to 31.5	53 to 56	0.385 to 0.387

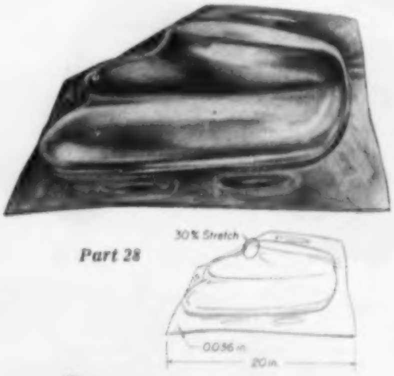
Grain Size

A sheet having grain size too large will exhibit a coarse granulated surface after deep drawing. This is known in the shop as "orange peel", and requires filing and polishing in order to obtain a smooth surface on the finished stamping. The magnitude of the orange peel effect is directly proportional to the grain size.

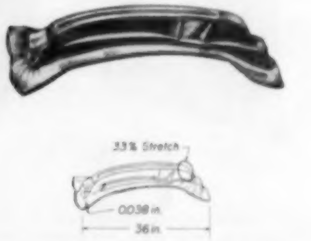
Steel with grain size too small is likely to have too high a yield point, tensile strength and hardness, and insufficient elongation. Maximum ductility is obtained in steel of ASTM grain size 8 (96 to 192 grains per sq in. at a magnification of 100 diam). A larger grain size can be tolerated in aluminum-killed steel.

Uniform grain size is desirable. A few very large grains scattered through

Stampings Typical of Severity Class 5 K(CR)



Part 28



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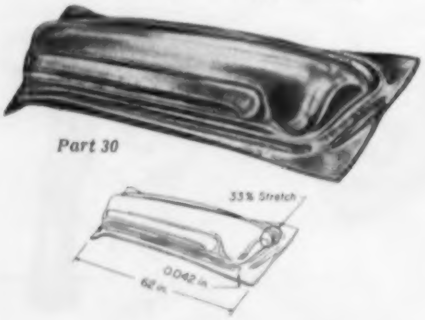
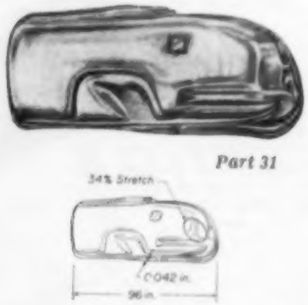


Part 30

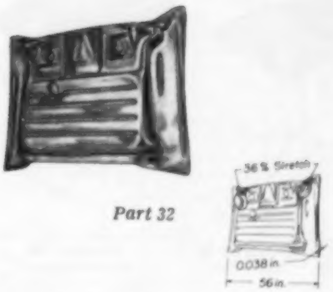


Part 31

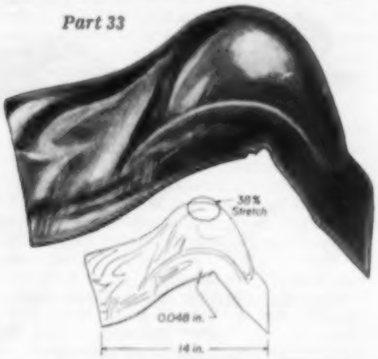
Part No.	Part Name	Exposed	Rockwell B Hardness	Olsen Cup, in.	Killed CR Steel Selected
28	Quarter panel extension......	Yes	47 max	0.385 min	DQ, tp
29	Lock pillar	No	47 max	0.390 min	DQ, tp
30	Tractor hood side.............	Yes	47 max	0.400 min	DQ, tp
31	Quarter panel	Yes	47 max	0.400 min	DQ, tp

Stampings Typical of Severity Class 6 K(CR)

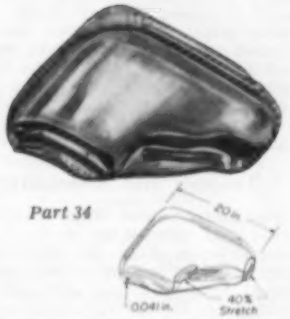
Part 32



Part 33



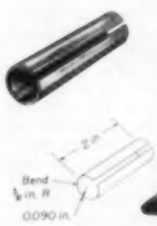
Part 34



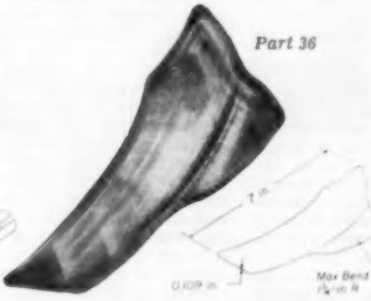
Part No.	Part Name	Exposed	Rockwell B Hardness	Olsen Cup, in.	Killed Cold Rolled Steel Selected
32	Cab floor pan	No	42 max	0.405 min	Drawing quality, temper passed
33	Grill bar	Yes	42 max	0.430 min	Drawing quality, temper passed
34	Fender skirt	Yes	42 max	0.412 min	Drawing quality, temper passed

Stampings Typical of Severity Class 1(HR)

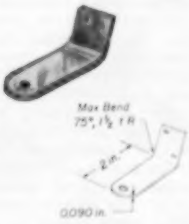
Part 35



Part 36



Part 37



Part No.	Part Name	Exposed	Rockwell B Hardness	Rimmed HR Steel Selected
35	Spacer	No	80 max	Commercial quality
36	Bracket	No	80 max	Commercial quality
37	Bracket	No	80 max	Commercial quality

a microstructure of the correct average grain size can result in rough surface.

A cored microstructure is sometimes observed in steel of inferior drawing quality. Such a structure has a definite band of medium-sized grains along each edge with very small grains in the center. The band is very low in carbon and impurities and corresponds to the rim of the ingot. The center is high in carbon and impurities and corresponds to the core of the ingot. Coring is usually confined to steel coming from the top part of the ingot, where segregation is most pronounced. Coring sometimes results when the finishing temperature is too low in the hot mill.

Variations in Thickness

Thickness variations in sheet steel can cause parts made on the same tooling to be of different shapes because of spring back or because the pressure applied is either insufficient or excessive at sharp corners or at sides that are to be held at a predetermined angle.

If the sheet is too thick, a die or roll adjusted to a certain thickness may pinch the steel and may localize the stretching, thus causing it to break; or it may work harden the steel and cause excessive spring back in a succeeding operation. Thickness greater than the die clearance may cause undesirable marring of the surface of the part or galling and scoring on the surface of the tools, and in some instances may be the reason for breakage of tools.

Standard tolerances on rolled sheet steel are given in the AISI Manual.

Surface Finish

Surface roughness of sheet steel has an effect on the finishing cost and the appearance of the formed product as well as on processing in dies and in other operations. Dull or slightly roughened surfaces are used especially in parts with the deepest draws to retain lubricant through the operations for minimum scoring of the dies and for better flow of metal over pressure pads. Sheet with a surface roughness of about 20 to 40 micro-in. performs well through dies and is smooth enough for most painted parts, such as hood tops and fenders, requiring average paint finish.

Table V evaluates the suitability of various surface roughnesses for finishing operations on products that require quality appearance and sales appeal. Single-dip or painted parts intended for trim and interior moldings require a smoother surface of about 10 to 20 micro-in., or class 2 in Table V. Sheet for average decorative chromium-plated parts should have surface roughness no greater than 10 micro-in. where the surface is to have no preparation except a light polishing to remove die marks. Parts with surface roughness as high as 15 micro-in. require extra surface preparation — for example, buffed copper plate applied before the regular plating sequence.

The selection of fine grained steel (ASTM 9) with minimum surface roughness from forming usually sacrifices some ductility and latitude in die design. With fine grain the steel will be somewhat harder, higher in yield point and elastic ratio, lower in elongation and uniform elongation. Die design should be such that the severity rating of the stamping is no worse than No. 4, and preferably No. 3.

Sheet for Vitreous Enameling. Flat parts and shallow draws require the selection of enameling sheet or ingot iron sheet having a typical composition of 0.015% C, 0.028% Mn, 0.005% P, 0.025% S and 0.003% Si, with the total of the five elements no greater than

Table V. Surface Classification of Sheet Steel

Class		Surface Roughness, micro-in.	Type of Finishing Applicable	Amount of Preparation Necessary
1	Extra Fine	Under 10	Plating	None
2	Fine	10 to 20	Plating Painting	Polishing None
3	Medium	20 to 30	Painting	Minimum
4	Medium Coarse	30 to 40	Painting	Moderate
6	Coarse	40 to 60	Painting	Considerable
9	Extra Coarse	Over 60	None(a)	(a)
10	Vitreous Enamel	Over 60	Vitreous Enamel	None

(a) No type of finish is applicable because of the very high cost of preparation that would be necessary.

0.10%. The surface of a vitreous enameled sheet has a rough appearance imparted by the heavily shot-blasted rolling mill roll; it should be ordered as VE (Vitreous Enamel) finish.

Cold rolled and hot rolled steel may be used on deep drawn parts, such as washing machine tubs, if the carbon content is held to 0.08% max. Cold rolled sheet should have VE finish, but in hot rolled steel a pickled surface is satisfactory.

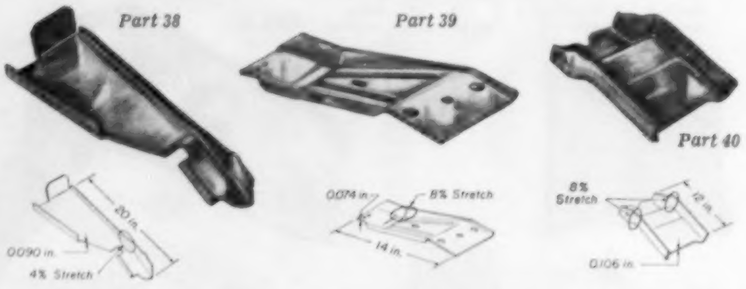
Tooling and Processing

Tool Development. When steel is received that will not make the part, it is either rejected outright or applied to another part of less severe requirements, subject to a rejection allowance, depending on the arrangements between fabricator and supplier. Small users may or may not have the practical alternative of diverting the steel to another part and may protect themselves accordingly in their purchasing arrangements. In addition, users should control the type of steel tryout stock furnished for tooling development. The procedure consists of selecting steels for tool development and die tryout that are below the average quality expected in regular production shipments. A steel should be selected near maximum hardness and near the minimum Olsen cup value for tentative severity classification of the part (Fig. 1).

Tools developed with steel of below-average quality are seldom troublesome and run with minimum tool breakage and steel rejection when the production run begins. They are also less sensitive to pressure adjustments and to variations in sheet thickness or to normal variations in steel properties, and maintenance costs are usually less. Conversely, tools developed with steel of above-average quality often prove unsatisfactory when forming regular production shipments of steel.

Die Design. In irregularly shaped parts, the angle at which the punch enters the lower die and the height of the blankholder in relation to the punch at the various locations should be such that the metal can flow snugly around the punch with a minimum of stretch. Poor design will allow wrinkles or buckles to form; to correct these will require additional blankholder pressure in local areas, thus increasing the stretch in the metal. As a result, the minimum mechanical property requirements and the cost of the sheet steel will be higher.

Stampings Typical of Severity Class 2(HR)



Part No.	Part Name	Exposed	Rockwell B Hardness	Rimmed HR Steel Selected
38	Hood hinge bracket............	No	68 max	Commercial quality
39	Cowl side reinforcement........	No	68 max	Commercial quality
40	Brake pedal support...........	No	68 max	Commercial quality

To save tooling costs, the final shape is often produced in one forming operation. In some stampings the final shape has sharp radii that localize the stretch and greatly increase the severity of forming. Frequently, to permit more forming in one operation, the radii can be greatly increased in the first forming die and can be as specified in a succeeding operation in combination with a trimming or flanging die. Little added tool cost is involved and forming is much less severe.

Some parts, such as the modern automobile front fender that cannot be made from flat sheet of any quality, must be preshaped and welded into the form of a cone at the front of the blank so that more metal is in the die before the blankholder closes, to reduce severity of stretching. As shown in Fig. 8, this permits the use of cold rolled steel compatible with severity class 4.

Where heavy stretching of a sheared edge cannot be avoided, extra quality will be required in the blanking die to produce the smoothest possible sheared edge. An example of such a part is the truck engine support shown among the stampings characteristic of class 4 for hot rolled steel on page 11. The most wear-resistant tool steel will be required; nevertheless, it will wear rapidly unless the burr side of the sheared edge is away from the tool face, which is sometimes the condition most susceptible to tearing during the stretch. The forming operation should precede the shearing operation wherever tool design and tooling cost permit. If this cannot be arranged, the forming operation should follow the shearing operation immediately to avoid aging problems. The steel along the edge should be the softest possible and in some instances may have to be stress relieved by hand torch or induction heating.

Poor maintenance of the die may necessitate using steel of a higher quality than was required for making parts in the unworn die. Blankholder dies worn to the point of uneven bearing will allow too much steel to slip through in some locations and not enough in others. When the resulting buckles or metal breakage begin to increase in production, the tooling must be checked and repaired, or steel of higher quality must be selected.

Speed of Forming has little effect on formability of steels used for the kind of simple bending or flanging or the moderate amount of stretching involved in severity classes 1, 2 and most of 3. The maximum velocity of the punch as it contacts the blank may be as high as about 200 fpm for parts in these severity classes.

However, the steels used for most of the parts in severity classes 4 and higher, and some of those for class 3, move considerably over the face of the punch or flow appreciably over the blankholder. The flow of the metal in such operations is controlled by frictional forces so sensitive to speed that the steel often stretches to failure before moving against the frictional forces, provided the punch velocity exceeds a critical value, which is different for each steel and die combination. Maximum punch velocity of 40 fpm is recommended for these stampings.

Reselection of the steel may sometimes be avoided when speed of draw becomes a problem. Frictional forces may be decreased by the use of lubricants at the punch face and in certain blankholder areas. If lubrication does not solve the problem, and the die and press program has already been designed for reduced friction at the beginning of the forming operation, then either the speed of the punch will have to be reduced as it contacts the blank or a steel of greater formability must be selected.

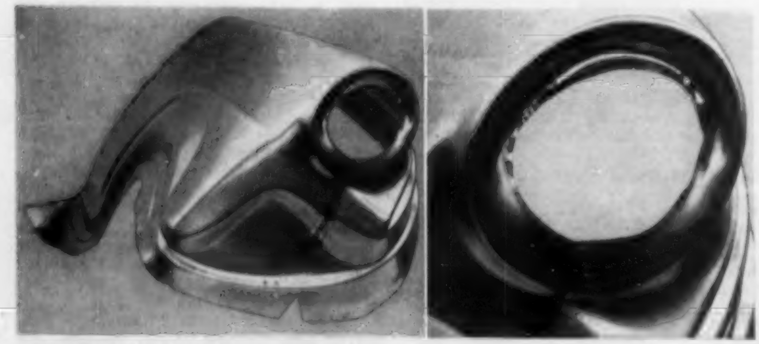


Fig. 8. Full and Close-Up Views of a Front Fender Showing the Area of Deepest Draw. Blank was preshaped and welded into the form of a cone at the front section before forming. This reduces the severity of stretching so that cold rolled steel compatible with severity class 4 can be used. Without preshaping, the part could not have been produced from sheet of any quality.

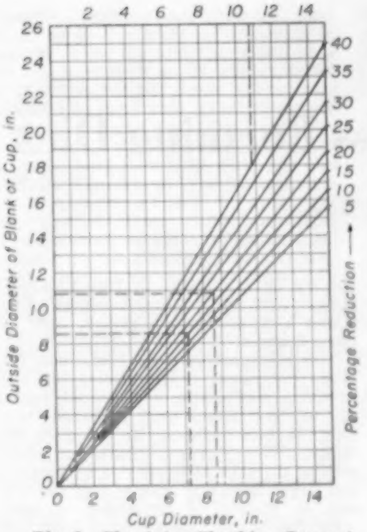


Fig. 9. Chart for Checking Percentage Reduction in Drawing of Cups

Lubrication. The type of lubricant usually has little effect on the grade of steel selected to form a given part. The main effect of a lubricant is to prevent die galling and die wear and to reduce the friction over critical areas, thus allowing proper flow of metal and possibly a reduction in severity class. The thicker gages and higher forming speeds require increasingly effective lubricants. When unpickled hot rolled steel is selected in heavy gages, the mill oxide with mineral oil lubricant of medium viscosity reduces galling and pickup in severe forming but markedly increases die wear. When hot rolled steel is selected with pickling specified, phosphate coating with soap solution applied will have the same effect, but without excessive die wear.

Minimum Bend Radius is a measure of the ability of the steel to deform without rupturing. The severity of deformation is proportional to the sharpness of bend and, for steels that will not make a sharp bend, the minimum radius is quoted in terms of the thickness (t) as listed in Table VI.

Table VI. Minimum Bend Radii for Sheet Steel

Class of Steel	Minimum Bend Radius, in. Parallel to Rolling Direction	Minimum Bend Radius, in. Transverse to Rolling Direction
Cold Rolled		
Commercial	0.01	0.01
Drawing, rimmed.....	0.01	0.01
Drawing, killed	0.01	0.01
Enameling	0.01	0.01
Cold Rolled, Special Properties		
¼ hard[(a)].............	1 t	½ t
½ hard[(b)].............	NR	1 t
Full hard[(c)]............	NR	NR
Hot Rolled		
Commercial, up to 0.090 in........	¾ t	½ t
Commercial, over 0.090 in.........	1½ t	1 t
Drawing, up to 0.090 in........	½ t	¼ t
Drawing, over 0.090 in.........	¾ t	½ t

(a) ¼ hard sheet has Rockwell B 60 to 75.
(b) ½ hard sheet has Rockwell B 70 to 85.
(c) Full hard sheet has Rockwell B 84 min.
NR means "not recommended."

Reduction of Drawn Cups is usually expressed as the percentage reduction from the diameter of the blank to the diameter of the cup. Thus, a cup of 6-in. diam drawn from a blank of 10-in. diam represents a percentage reduction of 40%.

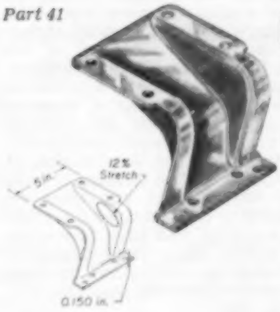
At the corner of the draw die or draw ring over which the steel slides in forming the cup, the radius must be large enough not to rupture the steel but not so large that the cup will have wrinkles. This radius should be 4 to 8 times the thickness of the blank in the first operation, using 1008 or 1010 commercial quality sheet steel 0.062 in. thick or less. The radius of the punch should be 6 to 12 times the blank thickness in operations of greatest reduction, but can be made sharper when reductions are about 5%. The larger punch radius is better with smaller die radius. Punch and die radii ordinarily cause problems only in reductions greater than 30%.

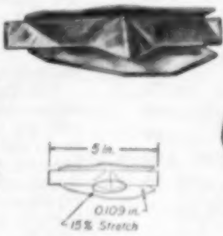
If the appearance of the cup is important, temper-passed steel should be specified; if not, annealed steel may be used.

A chart that correlates the percentage reduction with the blank size and cup size is shown in Fig. 9, which may be illustrated by an example in which the problem is to determine whether a cup of 7½-in. diam can be made in three draws of 40, 20 and 15% from an 18-in. diam blank. To find the diameter of the cup after the first draw, trace the 18-in. (blank diam) line horizontally until it intersects the diagonal line for 40% reduction. From this intersection, draw a vertical line to the top or bottom of the graph and read 10.8 in. for the outside diameter of the cup after the first draw. Next, for the 20% reduction in the second draw, trace a horizontal line from 10.8 on the vertical axis until it intersects the diagonal line for 20% reduction. From this point draw a vertical line to the bottom of the graph and read 8.6 in., which is the outside diameter of the cup after the second draw. The outside diameter of the cup after the third draw, assumed to be 15%, is found with the same procedure, by drawing a horizontal line from 8.6 to its intersection with the diagonal 15% line and from there to the bottom scale, which gives the reading 7¼ in. Hence, it is concluded that a 7½-in. diam cup can be drawn from an 18-in. blank in the three assumed reductions.

Stampings Typical of Severity Class 3(HR)

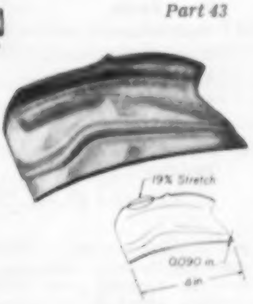
Part 41





Part 42

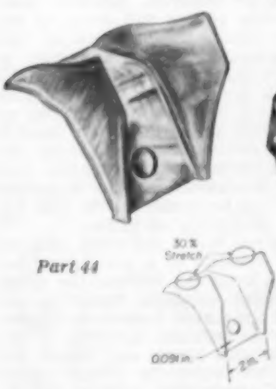
Part 43



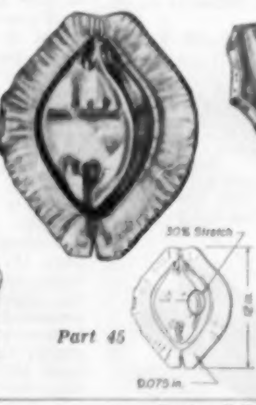
Part No.	Part Name	Exposed	Rockwell B Hardness	Rimmed HR Steel Selected
41	Truck frame brace............	No	65 max	Drawing quality
42	Reinforcement	No	60 max	Commercial quality
43	Reinforcement	No	60 max	Commercial quality

Stampings Typical of Severity Class 4(HR)

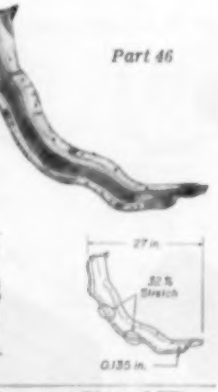
Part 44



Part 45



Part 46



Part No.	Part Name	Exposed	Rockwell B Hardness	Rimmed HR Steel Selected
44	Bracket	No	55 max	Drawing quality
45	Front fender filler..............	No	55 max	Drawing quality
46	Truck engine support..........	No	57 max	Drawing quality

The Selection of Material for Press Forming Dies

By the ASM Committee on Press Forming Dies

THIS ARTICLE deals with the selection of material for dies to form sheet metal in a press. The forming operations considered involve bending and mild or moderate stretching of the sheet. Dies for making deep-drawn cup-shaped objects, fenders and other severely stretched metal parts are not included here.

The selection of die material is based on the previous performance of similar tools in similar operations. This article summarizes such experience by indicating typical selections for 504 specific sets of conditions. From a study of the full range of these selections, the reader may gain an understanding of die materials that can be applied to a variety of similar selection problems.

The performance of a forming die is determined largely by wear. Total wear is affected primarily by the length of the production run and the severity of the forming operation. Hence, quantity is the principal variable shown in the accompanying selection tables, and the importance of severity is recognized by the inclusion of a separate table for each of six parts of different size or shape.

The metal being formed, its thickness, and the finish and dimensional tolerances required in the part are also influential factors and are included as additional variables in the tables.

The amount of wear on a given die material during forming is proportional to the distance the sheet metal slides over the die at a given pressure between the two surfaces in contact. Thin, soft or weak sheet metals exert the least pressure and thus cause the least wear; strong, thick metals cause the most rapid wear. However, the rate of wear for each combination of metals may be considerably different, depending on their surface characteristics, the speed of forming and type of lubrication. In forming parts with dies that produce wrinkles, very high localized pressures are developed on the tools, and attempts to iron out such wrinkles almost always produce prohibitively high rates of wear and galling.

Subdivisions

Sheet Thickness..............13
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Selection Tables for Parts of Mild Severity...........15
Selection Tables for Parts of Moderate Severity.......16
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Cast Iron.....................19
Zinc Alloy....................19
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4140 Alloy Steel..............20
Cast Steel....................20
Aluminum Bronzes...........20
Plastics 20

ASM-SLA T5, G1, TS, Zn

The recommendations made in this article are based on observed performance of a wide range of die materials in producing a great variety of parts. These recommendations are listed in the selection tables on pages 14 to 16, for six parts, shown in Fig. 1, which range from the simplest, such as parts 1 and 2, to moderately severe, such as parts 5 and 6.

The recommended die materials include the range from plastics for low production of simple to moderate parts, up to the most wear-resistant tool steels surface hardened by nitriding, for making severe parts. Parts of even greater severity or those run in quantities larger than one million may require dies or inserts of cemented carbide.

In the many instances where the tables show more than one material for the same conditions of tooling, the materials are listed in order of preference with regard to the expected cost per piece, but the ultimate choice will depend on availability more often than not, rather than on the small differences in performance or cost of the materials for a given set of conditions.

The Tools for Parts 1 and 2 (selection tables on page 14) consist of a punch and an upper and lower die. None of these die components would wear much, because there is little deformation of the sheet metal during forming of such extremely simple parts, and therefore there is little or no sliding of the sheet over the lower die and little movement over the punch. Thus, large quantities of such parts can be formed by tools made of any die material available in a convenient size.

Tooling for Part 3 (selection table on page 15) consists of a punch and lower die. In operation the punch pushes the blank through the lower die, which results in wear on the lower die. The metal envelops the punch closely with little sliding. Thus, the punch generally will produce ten times as many parts with the same wear as the lower die made of the same material. However, wear and possibly galling will occur at the areas of moderate shrinkage of this part, particularly when the part is formed on these single-action dies. For this small die, type D2 tool steel may be used for production quantities as low as 10,000, since the cost of steel is of minor importance for a small die. The high-carbon high-chromium tool steel has the advantage that if galling occurs it can be nitrided after trial, for effective prevention of galling.

Tooling for Part 4 (selection table on page 15) consists of a punch and an upper and lower die. Without the upper die, excessive wrinkling would be expected at the shrink flanges. As in part 3, less wear-resistant material is required for the punch and upper die than for the lower die. Under conditions for which tool steel is recom-

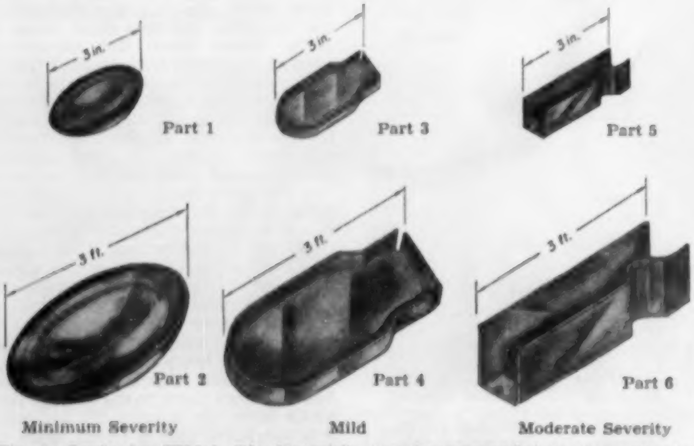


Fig. 1. Parts for Which Die Materials Are Recommended in the Selection Tables on Pages 13 to 16

This is a new subject in the ASM Metals Handbook mended for making part 4, the tool steel should be in the form of inserts in a cast iron lower die and the punch of a cast tool steel such as D2. For example, for 10,000 to 100,000 pieces a cast iron die might be used with A2 or D2 inserts at points of most wear. For quantities greater than 100,000 pieces or when this part must have close tolerances, the dies would have inserts of type D2 tool steel at all surfaces subject to wear. For quantities less than 100,000 the entire lower die would be made of the material indicated in the selection table, without inserts. The punch would be made of a less wear-resistant material, usually as indicated in the first column to the left of the quantity being considered

The Constriction in Parts 5 and 6 (selection tables on page 16) is produced by stretching rather than by shrinking of the metal along the constricted region, and the tooling therefore consists of a punch and lower die with no upper die required. The metal envelops the punch with minor sliding but produces about ten times more wear on the lower die than on the punch. Cast iron dies with inserts of type A2 or D2 tool steel would be needed for production of 10,000 parts or more. However, the same material is indicated for both the punch and lower die for part 5 in the selection table, page 16, because of the small size and the relatively minor cost of material.

In the selection table for part 6, the recommendations refer to the material to be used for the wearing edges of the lower die. The body of the lower die would be made of cast iron with wearing edges of tool steel in those instances where tool steel is recommended in the table. The punch for making part 6 could be of a material about one tenth as wear resistant as tool steel — for example, alloy cast iron. For a quantity large enough to require a punch material of greater wear resistance than alloy cast iron or cast steel, a tool steel insert should be used at the constricted section.

Sheet Thickness

Thick sheets of any metal will exert greater pressure on the dies than thin sheets of the same metal. The tables, pages 14 to 16, list selections only for sheets 0.050 in. thick. Table I, below, recommends materials for dies to make parts 3 and 4 in three sizes from sheet of four different thicknesses. The selections in Table I illustrate the increasing effect of galling and wear as parts are made from thicker sheets—especially parts with shrink flanges as illustrated.

Table I deals only with die materials for forming steel parts. The forming pressure depends not only on the thickness but also on the strength of the sheet being formed. Wear and galling are less severe with any thickness of soft metal, such as aluminum and copper alloys, than with low-carbon steel, but more severe with high-strength metals such as stainless steels and heat-resisting alloys.

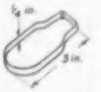
Size of Part

For small stampings such as parts 1, 3 and 5, cast or plastic dies are uneconomical unless made from a model already available and with only minor finishing operations required on the dies. When the cost of patternmaking is included, cast or plastic dies will usually be more expensive than dies machined from other materials. The cost of the steel is usually a small fraction of the cost of dies for a small part, and the availability of material in a size that will minimize machining on the dies will usually be a greater factor in cost than any other.

As the size of the part increases, the cost savings resulting from minimizing machining by use of a casting close to

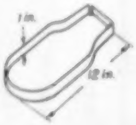
Table I. Recommended Materials for Lower Die for Forming Steel Parts of Three Sizes, Each in Four Thicknesses
(Assuming No Finish or Tolerance Requirements)

Sheet Thickness, in.	Recommended Lower Die Material[a]					
	Total Quantity of Parts to be Produced					
	10[b]	100	1,000	10,000	100,000[c]	1,000,000[c]
			For Part 3, Maximum Dimension of 3 In.			
0.031	Mild steel and 4140	Mild steel and 4140	Mild steel and 4140	Mild steel and 4140	4140, mild steel chromium plated, D2	D2
0.062	Mild steel and 4140	Mild steel and 4140	Mild steel and 4140	Mild steel and 4140	4140, mild steel chromium plated, D2	D2
0.125	Mild steel and 4140	Mild steel and 4140	Mild steel and 4140	Mild steel, 4140 and A2	D2	D2
0.250	Mild steel and 4140	Mild steel and 4140	Mild steel and 4140	A2 and D2	D2	D2
			For a 12-In. Part Similar to Parts 3 and 4			
0.031	Mild steel, 4140 and zinc alloy	Mild steel, 4140 and zinc alloy	Mild steel, 4140 and zinc alloy	Mild steel, 4140, zinc alloy and alloy cast iron	Alloy cast iron,[d] mild steel chromium plated, 4140	D2
0.062	Mild steel, 4140 and zinc alloy	Mild steel, 4140 and zinc alloy	Mild steel, 4140 and zinc alloy	Mild steel, 4140, zinc alloy and alloy cast iron	Alloy cast iron[d] and A2	D2
0.125	Mild steel, 4140 and zinc alloy	Mild steel, 4140 and zinc alloy	Mild steel, 4140 and cast iron	Mild[d] and A2 steels	A2 and D2	D2
0.250	Mild steel and 4140	Mild steel, 4140 and cast iron	Mild steel and alloy cast iron	Mild[d] and A2 steels	A2 and D2	D2
			For Part 4, Maximum Dimension of 36 In.			
0.031	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass, polyester-glass, zinc alloy	Epoxy or polyester-glass,[e] alloy cast iron, zinc alloy[e]	Alloy cast iron[d]	D2
0.062	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass, polyester-glass, zinc alloy	Epoxy or polyester-glass,[e] alloy cast iron, zinc alloy[e]	A2	D2
0.125	Zinc alloy	Zinc alloy	Zinc alloy, cast iron	Alloy cast iron[d]	A2 and D2	D2
0.250	Zinc alloy, cast iron	Zinc alloy, cast iron	Alloy cast iron	Alloy cast iron[d]	A2 and D2	D2

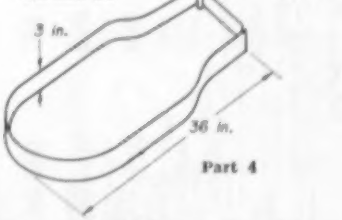


Part 3. For a sketch of the die for this part, see Fig. 2.

A 12-in. part similar in shape to parts 3 and 4. For a sketch of the die for this part see Fig. 2. The cost of tooling this part is given in Table II, page 17.



Part 4. Tooling for this part consists of a punch and an upper and lower die and is shown in the sketch of Fig. 3 on page 17.

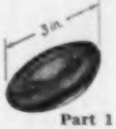


Part 4

(a) See Table III, page 19, for description of materials. Materials recommended in above table are for forming parts from low-carbon steel; wear and galling will be less with aluminum and copper alloys, and more with stainless and heat-resisting alloys than with low-carbon steel. (b) Ten or the minimum quantity that justifies tooling. (c) All A2 or D2 tool steels nitrided after tryout if required. (d) Inserts of A2 tool steel are recommended for wear edges for the shrink flange. (e) With inserts

Selection Table for Part 1. Recommended Punch Material for Forming a Small Part of Minimum Severity

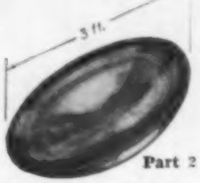
Part (Made of 0.050-In. Sheet)	Requirements			Recommended Punch Material(a)					
				Total Quantity of Parts to be Formed					
Metal Being Formed	Finish	Tolerance, in.	Lubrication(b)	10(c)	100	1,000	10,000	100,000	1,000,000
2S Aluminum, brass, copper(d)	None	None	Yes	Nylon-metal, mild steel	Epoxy-metal, mild steel	Epoxy-metal, polyester-metal, mild steel	Epoxy,(e) polyester,(e) mild steel	Polyester-glass,(e) mild steel	O1, A2 tool steels
2S Aluminum, brass, copper(d)	Best	None	No	Nylon-metal, mild steel	Epoxy-metal, mild steel	Epoxy-metal, polyester-metal, mild steel	Epoxy,(e) polyester,(e) mild steel	Polyester-glass,(e) mild steel	O1, nitrided A2
Magnesium or titanium(f)	Best	None	Yes	Mild steel	Mild steel	Mild steel	Mild steel	Mild steel	O1, nitrided A2
Low-carbon steel, to ¼ hard	None	None	Yes	Epoxy-metal, polyester-metal, mild steel	Epoxy-metal, polyester-metal, mild steel	Epoxy-glass-metal, polyester-glass-metal, mild steel	Polyester-glass,(e) mild steel	Mild steel	O1, A2 tool steels
Type 300 stainless, to ¼ hard	None	None	Yes	Epoxy-metal, polyester-metal, mild steel	Epoxy-metal, polyester-metal, mild steel	Epoxy-glass-metal, polyester-glass-metal, mild steel	Polyester-glass,(e) mild steel	Mild steel	O1, A2 tool steels
Low-carbon steel	Best	None	Yes	Epoxy-metal, polyester-metal, mild steel	Epoxy-metal, polyester-metal, mild steel	Epoxy-glass-metal, polyester-glass-metal, mild steel	Polyester-glass,(e) mild steel	Mild steel	O1, nitrided A2
High-strength aluminum or copper alloys	Best	None	No	Epoxy-metal, polyester-metal, mild steel	Epoxy-metal, polyester-metal, mild steel	Epoxy-glass-metal, polyester-glass-metal, mild steel	Polyester-glass,(e) mild steel	Mild steel	O1, nitrided A2
Type 300 stainless, to ¼ hard	Best	None	Yes	Epoxy-metal, polyester-metal, mild steel	Epoxy-metal, polyester-metal, mild steel	Epoxy-glass-metal, polyester-glass-metal, mild steel	Polyester-glass,(e) mild steel	O1, nitrided A2	O1, nitrided A2
Heat-resisting alloys	Best	None	No	Epoxy-metal, polyester-metal, mild steel	Epoxy-metal, polyester-metal, mild steel	Polyester-glass-metal, mild steel	Polyester-glass,(e) mild steel	O1, nitrided A2	O1, nitr A2
Type 300 stainless, to ¼ hard	Best	None	No	Epoxy-metal, polyester-metal, mild steel	Epoxy-metal, polyester-metal, mild steel	Epoxy-glass-metal, polyester-glass-metal, mild steel	Polyester-glass,(e) mild steel	O1, nitrided A2	O1, nitr A2



Part 1

Selection Table for Part 2. Recommended Punch Material for Forming a Large Part of Minimum Severity

2S Aluminum, brass, copper(d)	None	None	Yes	Nylon-metal, zinc alloy	Epoxy-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy,(e) polyester,(e) zinc alloy	Polyester-glass,(e)(g) zinc alloy	Cast iron
2S Aluminum, brass, copper(d)	Best	None	No	Epoxy-metal, zinc alloy	Epoxy-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy,(e) polyester,(e) zinc alloy	Zinc alloy	Cast iron
Magnesium or titanium(f)	Best	None	Yes	Zinc alloy	Zinc alloy	Cast iron	Cast iron	Cast iron	Alloy cast iron
Low-carbon steel, to ¼ hard	None	None	Yes	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass-metal, polyester-glass-metal, zinc alloy	Polyester-glass,(e) zinc alloy	Cast iron	Alloy cast iron
Type 300 stainless, to ¼ hard	None	None	Yes	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass-metal, polyester-glass-metal, zinc alloy	Polyester-glass,(e) zinc alloy	Cast iron	Alloy cast iron
Low-carbon steel	Best	None	Yes	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass-metal, polyester-glass-metal, zinc alloy	Polyester-glass,(e) zinc alloy	Cast iron	Alloy cast iron
High-strength aluminum or copper alloys	Best	None	No	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass-metal, polyester-glass-metal, zinc alloy	Polyester-glass,(e) zinc alloy	Cast iron	Cast iron
Type 300 stainless, to ¼ hard	Best	None	Yes	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass-metal, polyester-glass-metal, zinc alloy	Cast iron	Alloy cast iron	Alloy cast iron
Heat-resisting alloys	Best	None	No	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass-metal, polyester-glass-metal, zinc alloy	Cast iron	Alloy cast iron	Alloy cast iron
Type 300 stainless, to ¼ hard	Best	None	No	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass-metal, polyester-glass-metal, zinc alloy	Cast iron	Alloy cast iron	Alloy cast iron



Part 2

(a) Description of materials is given in Table III, page 19. When more than one material for the same conditions of tooling is given, the materials are listed in order of cost preference with the least expensive being first; however, the final choice often will depend on availability rather than on small differences in cost or performance of the materials. (b) Refers to specially applied lubrication rather than mill oil. (c) Ten or the minimum quantity that justifies tooling. (d) Soft. (e) With inserts. (f) Heated sheet. (g) Some die maintenance will be needed before the stated quantity has been produced.

For information concerning the effect of sheet thickness on selection of die materials, see Table I, page 13. For information on the cost of tooling, see Table II, page 17.

Selection Table for Part 3. Recommended Lower Die Material for Forming a Small Part of Mild Severity

Part (Made of 0.050-In. Sheet) Metal Being Formed	Requirements Finish	Requirements Tolerance, in.	Requirements Lubrication(b)	Recommended Lower Die Material(a) Total Quantity of Parts to be Formed 10(c)	100	1,000	10,000	100,000	1,000,000
2S Aluminum, brass, copper(d)	None	None	Yes	Nylon-metal, mild and 4140 steel	Epoxy-metal, mild and 4140 steel	Polyester-metal, mild and 4140 steel	Polyester-glass,(e) mild and 4140 steel	Mild and 4140 steel	A2, D2 tool steel
2S Aluminum, brass, copper(d)	None	±0.005 R	Yes	Epoxy-metal, mild and 4140 steel	Epoxy-metal, mild and 4140 steel	Polyester-metal, mild and 4140 steel	Polyester-glass,(e) mild and 4140 steel	4140 or O1, A2, D2 tool steel	A2, D2 tool steel
2S Aluminum, brass, copper(d)	Best	±0.005 R	Yes	Epoxy-metal, mild and 4140 steel	Epoxy-metal, mild and 4140 steel	Polyester-metal, mild and 4140 steel	Polyester-glass,(e) mild and 4140 steel	4140 or O1, A2 nitrided D2	A2, nitrided D2
Magnesium or titanium(f)	Best	±0.005 R	Yes	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	A2, nitrided D2	A2, nitrided D2	A2, nitrided D2
Low-carbon steel, to ¼ hard	None	None	Yes	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	4140, mild steel chromium plated, D2	D2 tool steel	D2 tool steel
Type 300 stainless, to ¼ hard	None	None	Yes	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	D2 tool steel	D2 tool steel
Low-carbon steel	Best	±0.005 R	Yes	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	Nitrided D2	Nitrided D2
High-strength aluminum or copper alloys	Best	±0.005 R	No(g)	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	Mild steel chromium plated and 4140	Mild steel Cr plated, 4140, O1, nitrided A2	Nitrided D2
Type 300 stainless, to ¼ hard	None	±0.005 R	Yes	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	Mild steel chromium plated and 4140	4140 or O1, A2	D2 tool steel
Type 300 stainless, to ¼ hard	Best	±0.005 R	Yes	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	Mild steel chromium plated, nitrided D2	Nitrided D2	Nitrided D2
Heat-resisting alloys	Best	±0.005 R	Yes	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	Mild steel chromium plated, nitrided D2	Nitrided D2	Nitrided D2
Low-carbon steel	Good	±0.005 R	No(g)	Mild and 4140 steel	Mild and 4140 steel	Mild and 4140 steel	Mild steel chromium plated, nitrided D2	Nitrided D2	Nitrided D2

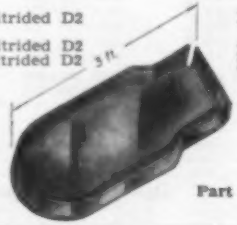
Part 3

Selection Table for Part 4. Recommended Lower Die Material for Forming a Large Part of Mild Severity

Part (Made of 0.050-In. Sheet) Metal Being Formed	Requirements Finish	Requirements Tolerance, in.	Requirements Lubrication(b)	Recommended Lower Die Material(a) Total Quantity of Parts to be Formed 10(c)	100	1,000	10,000	100,000	1,000,000
2S Aluminum, brass, copper(d)	None	None	Yes	Nylon-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Polyester-metal, zinc alloy	Epoxy or polyester-glass,(e) zinc alloy	Alloy cast iron	Alloy cast steel
2S Aluminum, brass, copper(d)	None	±0.005 R	Yes	Nylon-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Polyester-metal, zinc alloy	Alloy cast iron	Alloy cast steel	Alloy cast steel
2S Aluminum, brass, copper(d)	Best	±0.005 R	Yes	Nylon-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Polyester-metal, zinc alloy	Alloy cast iron	Alloy cast steel	Alloy cast steel
Magnesium or titanium(f)	Best	±0.005 R	Yes	Cast iron, zinc alloy	Cast iron, zinc alloy	Cast iron, zinc alloy	Cast iron	Alloy cast iron, alloy cast steel	Alloy cast iron, alloy cast steel
Low-carbon steel, to ¼ hard	None	None	Yes	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass, polyester-glass, zinc alloy	Epoxy or polyester-glass,(e) alloy cast iron	A2 tool steel	D2 tool steel
Type 300 stainless, to ¼ hard	None	None	Yes	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-metal, polyester-metal, zinc alloy	Epoxy-glass, polyester-glass, zinc alloy	Epoxy or polyester-glass,(e) alloy cast iron	A2 tool steel	D2 tool steel
Low-carbon steel	Best	±0.005 R	Yes	Zinc alloy	Zinc alloy	Epoxy-glass, polyester-glass, zinc alloy	Alloy cast iron	Nitrided A2	Nitrided D2
High-strength aluminum or copper alloys	Best	±0.005 R	No(g)	Zinc alloy	Zinc alloy	Polyester-glass, zinc alloy	Alloy cast steel	Alloy cast steel	Nitrided D2
Type 300 stainless, to ¼ hard	None	±0.005 R	Yes	Zinc alloy	Zinc alloy	Zinc alloy	Alloy cast iron	D2 tool steel	D2 tool steel
Type 300 stainless, to ¼ hard	Best	±0.005 R	Yes	Zinc alloy	Zinc alloy	Zinc alloy	Aluminum bronze	Nitrided D2	Nitrided D2
Heat-resisting alloys	Best	±0.005 R	Yes	Zinc alloy	Zinc alloy	Aluminum bronze	Aluminum bronze	Nitrided D2	Nitrided D2
Low-carbon steel	Good	±0.005 R	No(g)	Zinc alloy	Zinc alloy	Aluminum bronze	Aluminum bronze	Nitrided D2	Nitrided D2

(a) Description of materials is given in Table III. When more than one material for the same conditions of tooling is given, the materials are listed in order of increasing cost; however, the final choice often will depend on availability rather than on small differences in cost or performance. Under conditions for which tool steel is recommended for making part 4, the lower die should be of cast iron with inserts of wrought tool steel and the punch of a cast tool steel such as D2. For example, for 10,000 to 100,000 pieces a cast iron die might be used with A2 or D2 inserts at the shrink flanges shown in the illustration; for more than 100,000 pieces the dies would have inserts of type D2 at all surfaces subject to wear. (b) Refers to specially applied lubrication rather than mill oil. (c) Ten or the minimum quantity that justifies tooling. (d) Soft. (e) With inserts. (f) Heated sheet. (g) Lubrication should be used to make 1 to 1000 parts.

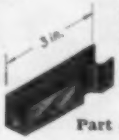
For the effect of sheet thickness on selection of die materials for making Parts 3 and 4, see Table I, page 13. For information on the cost of tooling to make these two parts, see Table II, page 17.



Part 4

Selection Table for Part 5. Recommended Lower Die Material for Forming a Small Part of Moderate Severity

Part (Made of 0.050-In. Sheet)	Requirements			Recommended Lower Die Material(a) — Total Quantity of Parts to be Formed					
Metal Being Formed	Finish	Tolerance, in.	Lubrication(b)	10(c)	100	1,000	10,000	100,000	1,000,000
2S Aluminum, brass, copper(d)	None	None	Yes	Mild steel	Mild steel	Mild steel	Mild steel	O1, nitrided A2 tool steel	O1, nitrided A2 tool steel
2S Aluminum, brass, copper(d)	None	±0.020 R	Yes	Mild steel	Mild steel	Mild steel	Mild steel	O1, nitrided A2 tool steel	O1, nitrided A2 tool steel
2S Aluminum, brass, copper(d)	Best	±0.020 R	Yes	Mild steel	Mild steel	Mild steel	Mild steel	O1, nitrided A2 tool steel	O1, nitrided A2 tool steel
Magnesium or titanium(e)	Best	±0.020 R	Yes	Mild steel	Mild steel	Mild steel	O1, nitrided A2	Nitrided D2	Nitrided D2
Low-carbon steel, to ¼ hard	None	None	Yes	Mild steel, A2 tool steel	Mild steel, A2 tool steel	Mild steel, A2 tool steel	Mild steel chromium plated, D2	Mild steel, chromium plated, D2	D2 tool steel
Type 300 stainless, to ¼ hard	None	None	Yes	Mild steel, A2 tool steel	Mild steel, A2 tool steel	Mild steel, A2 tool steel	Mild steel chromium plated, D2	Mild steel, chromium plated, D2	D2 tool steel
Low-carbon steel	Best	±0.020 R	Yes	Mild steel, O1 or nitrided A2	Mild steel, O1 or nitrided A2	Mild steel, O1 or nitrided A2	Mild steel chromium plated, D2	Mild steel, chromium plated, nitrided D2	Nitrided D2
High-strength aluminum or copper alloys	Best	±0.020 R	No(f)	Mild steel, nitrided A2	Mild steel, nitrided A2	Mild steel, nitrided A2	Nitrided A2	Nitrided A2	Nitrided D2
Type 300 stainless, to ¼ hard	None	±0.020 R	Yes	Mild steel, A2 tool steel	Mild steel, A2 tool steel	Mild steel, A2 tool steel	Mild steel chromium plated, D2	D2 tool steel	D2 tool steel
Type 300 stainless, to ¼ hard	Best	±0.020 R	Yes	Mild steel, nitrided A2	Mild steel, nitrided A2	Mild steel, nitrided D2	Mild steel chromium plated, nitrided D2	Nitrided D2	Nitrided D2
Heat-resisting alloys	Best	±0.020 R	Yes	Nitrided D2	Nitrided D2	Nitrided D2	Nitrided D2	Nitrided D2	Nitrided D2
Low-carbon steel	Good	±0.020 R	No(f)	Mild steel, nitrided A2	Mild steel, nitrided A2	Mild steel, nitrided A2	Nitrided D2	Nitrided D2	Nitrided D2



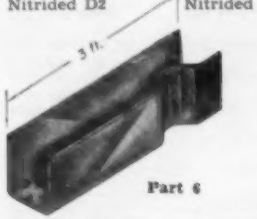
Part 5

Selection Table for Part 6. Recommended Lower Die Material for Forming a Large Part of Moderate Severity

2S Aluminum, brass, copper(d)	None	None	Yes	Zinc alloy	Zinc alloy	Zinc alloy	Cast iron	Cast iron	D2 tool steel A2 tool steel
2S Aluminum, brass, copper(d)	None	±0.031 R	Yes	Zinc alloy	Zinc alloy	Zinc alloy	Cast iron, cast steel	Cast steel, D2 tool steel	D2 tool steel A2 tool steel
2S Aluminum, brass, copper(d)	Best	±0.031 R	Yes	Zinc alloy	Zinc alloy	Zinc alloy	Cast iron, cast steel	Cast steel, nitrided D2	A2, nitrided D2
Magnesium or titanium(e)	Best	±0.031 R	Yes	Zinc alloy	Zinc alloy	Alloy cast iron	Alloy cast iron	Nitrided D2	Nitrided D2
Low-carbon steel, to ¼ hard	None	None	Yes	Zinc alloy	Zinc alloy	Alloy cast iron	Alloy cast iron	D2 tool steel	D2 tool steel
Type 300 stainless, to ¼ hard	None	None	Yes	Zinc alloy	Zinc alloy	Alloy cast iron	Alloy cast iron	D2 tool steel	D2 tool steel
Low-carbon steel	Best	±0.031 R	Yes	Zinc alloy	Zinc alloy	Alloy cast iron	A2, nitrided D2	Nitrided D2	Nitrided D2
High-strength aluminum or copper alloys	Best	±0.031 R	No(f)	Zinc alloy	Zinc alloy	Zinc alloy	Alloy cast iron	Nitrided D2	Nitrided D2
Type 300 stainless, to ¼ hard	None	±0.031 R	Yes	Zinc alloy	Zinc alloy	Zinc alloy	Aluminum bronze	D2 tool steel	D2 tool steel
Type 300 stainless, to ¼ hard	Best	±0.031 R	Yes	Zinc alloy	Zinc alloy	Aluminum bronze	Nitrided D2	Nitrided D2	Nitrided D2
Heat-resisting alloys	Best	±0.031 R	Yes	Zinc alloy	Zinc alloy	Aluminum bronze	Nitrided D2	Nitrided D2	Nitrided D2
Low-carbon steel	Good	±0.031 R	No(f)	Zinc alloy	Zinc alloy	Aluminum bronze	Nitrided D2	Nitrided D2	Nitrided D2

(a) Description of material is given in Table III, page 19. When more than one material for the same conditions of tooling is given, the materials are listed in order of increasing cost; however, the final choice often will depend on availability rather than on the small differences in cost or performance. Cast iron dies with inserts of type A2 or D2 tool steel would be needed for making 10,000 parts; however, the same material is recommended for punch and lower die for part 5 because of the small size and minor cost of material. Recommendations for making part 6 are the materials for the wearing edges of the lower die; body of the lower die would be of cast iron with wearing edges of the tool steel recommended; the punch could be of a material about one tenth as wear-resistant as tool steel. (b) Refers to specially applied lubrication rather than mill oil. (c) Ten or the minimum quantity that justifies tooling. (d) Soft. (e) Heated sheet. (f) Lubrication should be used to make 1 to 1000 parts.

For information concerning the effect of sheet thickness on selection of die materials, see Table I on page 13. For information on the cost of tooling to make parts of different sizes, see Table II, page 17.



Part 6

final size will more than offset the cost of a pattern. However, inserts of tool steel or carbide must be used on high-production dies subject to severe wear and galling. The selection of both the material and the locations of the inserts should be on the conservative side in those instances where production must not be interrupted for alteration of the tooling. If tools may be taken out of production, cast iron dies may be used with the wear surface flame-hardened and inserts added later if needed.

Cost of Tooling

Table II shows the relative cost of dies for forming parts such as No. 3 and 4 in sizes of 3, 12 and 36 in. The cost covers only the basic die components indicated; accessories such as gages, knockouts, wipers, guards, blankholder plates and the like have been omitted because they do not affect the comparison of cost. For the 3-in. and 12-in. parts the die consists of punch, ring and floater only, as shown in Fig. 2; for the 36-in. part, the die consists of a punch with upper and lower dies as shown in Fig. 3.

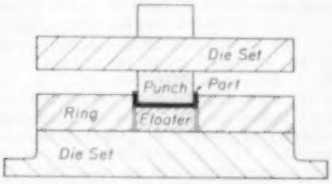


Fig. 2. Die for Tables I and II, 3-In. and 12-In. Parts

In one set of dies shown in Table II, the lower die had inserts of A2 tool steel; in another, D2 tool steel inserts were used; in both sets the punch was made of cast steel without inserts.

Cost of a pattern was included for the 3-in. plastic die. If this pattern were already available from some other operation and could be used without added expense for making the die, the cost would be reduced from $197 to $155.

For the 36-in. part, costs are not shown for hot rolled mild steel because distortion in heat treatment makes this size impracticable. Alloy steel 4140 was omitted because it is not generally available in this large size.

Quantity

The number of parts to be produced is an important factor in large dies in which the cost of material is equal to or greater than the cost of machining. In dies smaller than about 6 in. the difference between the cost of the most expensive and cheapest steels is less important than the assurance of long life without the necessity for rebuilding tools if the quantity should be in-

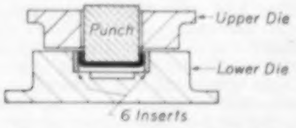


Fig. 3. Die for Tables I and II, 36-In. Part

Table II. Relative Cost of Tooling to Form Parts 3 and 4 and a Similar Part 12 In. in Maximum Dimension

(Tools Are Shown in Fig. 2 and 3 at Left)

Item	Cost of Die Components[a] Die Set	Punch	Ring	Floater	All Others	Template	Pattern	Totals
Tooling for Part 3, Maximum Dimension of 3 In. (See Fig. 2)								
Solid D2 Tool Steel								
Material	$31	...	$ 18	...	$ 2	....	....	$ 51
Labor	30	$60	100	$25	10	....	....	225
Total	61	60	118	25	12	....	....	276
Solid A2 Tool Steel								
Material	31	...	12	...	2	....	....	45
Labor	30	50	80	25	10	....	....	195
Total	61	50	92	25	12	....	....	240
Unalloyed Gray Cast Iron								
Material	31	...	3	...	1	....	....	35
Labor	30	35	50	25	10	....	....	150
Total	61	35	53	25	11	....	....	185
Hot Rolled Mild Steel, Carburized								
Material	31	...	1	...	1	....	....	33
Labor	30	40	60	25	10	....	....	165
Total	61	40	61	25	11	....	....	198
4140 Alloy Steel								
Material	31	...	2	...	1	....	....	34
Labor	30	40	60	25	10	....	....	165
Total	61	40	62	25	11	....	....	199
Epoxy-Metal[b]								
Material	31	...	3	...	1	....	$ 2	37
Labor	30	...	80	...	10	....	40	160
Total	61	...	83	...	11	....	42	197

Item	Cost of Die Components[a] Die Set	Punch	Ring	Floater	All Others	Template	Pattern	Totals
Tooling for a 12-In. Part Similar to Parts 3 and 4 (See Fig. 2)								
Cast Iron with Inserts of D2 Tool Steel								
Material	$50	...	$107	...	$ 5	....	....	$162
Labor	40	$100	310[c]	$50	20	....	....	520
Total	90	100	417	50	25	....	....	682
Cast Iron with Inserts of A2 Tool Steel								
Material	50	...	72	...	5	....	....	127
Labor	40	80	290[d]	50	20	....	....	480
Total	90	80	362	50	25	....	....	607
Unalloyed Gray Cast Iron								
Material	50	...	18	...	2	....	....	70
Labor	40	65	120	50	20	....	....	295
Total	90	65	138	50	22	....	....	365
Hot Rolled Mild Steel, Carburized								
Material	50	...	13	...	2	....	....	65
Labor	40	70	130	50	20	....	....	310
Total	90	70	143	50	22	....	....	375
4140 Alloy Steel								
Material	50	...	32	...	2	....	....	84
Labor	40	70	130	50	20	....	....	310
Total	90	70	162	50	22	....	....	394
Epoxy-Metal[b]								
Material	50	15	...	....	2	....	$ 5	72
Labor	40	120	...	....	15	....	60	235
Total	90	135	...	....	17	....	65	307

Item	Cost of Die Components[a] Punch	Upper Die Blankholder	Lower Die Blankholder	Lower Die Inserts	All Others	Template	Pattern	Totals
Tooling for Part 4, Maximum Dimension of 36 In. (See Fig. 3)								
Cast Iron with Inserts of D2 Tool Steel								
Material	$224	$ 88	$172	$233	$ 8	...	$ 12	$ 737
Labor	240	230	240	340	80	$40	280	1450
Total	464	318	412	573	88	40	292	2187
Cast Iron with Inserts of A2 Tool Steel								
Material	224	88	172	151	8	...	12	655
Labor	240	230	240	280	80	40	280	1390
Total	464	318	412	431	88	40	292	2045
Unalloyed Gray Cast Iron								
Material	100	51	110	....	5	...	12	278
Labor	200	220	310	....	80	40	280	1130
Total	300	271	420	....	85	40	292	1408
Zinc Alloy (Zn-Al-Cu-Mg)								
Material	Pattern, $325		Metal, 3450 lb at $0.2525 per lb					1196[e]
Labor	Foundry, $330		Machining, $200; spotting and fitting, $400					930
Total	....		....					2126[e]

(a) The cost of labor was computed at $5 per hr. (b) Costs listed under punch for epoxy-metal include ring and floater also. (c) The labor cost for making the inserts is $180. (d) The labor cost for making the inserts is $160. (e) Allowing 65% scrap value for the metal reduces total cost from $2126 to $1389.

creased above original expectations, or if the die material should prove to have been underspecified. However, for large dies both the choice of tool material and the design of the dies depend on the number of parts to be produced, particularly when quantities exceed 1000 parts.

On parts such as No. 6 in which there is considerable movement of the sheet over die surfaces, greatly increased die wear is likely. With such parts die inserts can be shimmed to allow for wear of the die, whereas, a solid die cannot be adjusted readily for wear. Therefore, risks may be taken in the selection of steel for inserts on jobs where production can be interrupted for this operation. However, if the insert is small the cost of material may be of much less consequence than the cost of diemaking and shimming, which may run from $10 to $100 per hr for lost time of the press, plus labor. Thus, it may be uneconomical to specify cheap steel for inserts.

Adjustable inserts are often impracticable for small dies. Therefore for high-production dies working under severe wear conditions and producing parts to close tolerances, it is often desirable to use a complete insert or to make the entire die of extremely wear-resistant material such as D2 tool steel nitrided or cemented carbide.

Tolerance Requirements

Tolerance requirements of the part may have an important effect on the choice of tool material when the part is to be finished without restriking. If the part is to be restruck, the material used in the restriking die is of less importance, because it usually will not be subjected to as much wear as the die that completes the primary operation. A major factor in the choice between a wear-resistant material and a less costly and less wear-resistant material is the necessity for maintenance during the production run.

Work Metal

The sheet metals of higher hardness usually will wear dies more rapidly, but other factors, such as the presence of scale on the surface of hot rolled, unpickled steels, will cause two to five times more wear. However, scaled surfaces cause less galling, which on tool materials may be an even more serious condition than wear, because galling or "pickup" on dies will cause repeated interruptions for reconditioning the die.

Soft brass and aluminum cause less wear and galling than carbon steel, while stainless steels and heat-resisting alloys cause more wear and galling. Where galling is anticipated, it is desirable to use materials such as D2 tool steel that can be treated subsequently, if necessary, to eliminate the difficulty. Possible treatments include chromium plating of any hardened steel, the hardening of alloy cast iron and the nitriding of tool steels such as type A2 and D2, which are preferable for nitriding because of the presence of nitride formers such as chromium and molybdenum in the steels.

Lubrication

In making parts at low and medium production (up to 10,000 pieces) it is often economical to use lubricants. With zinc dies, it is necessary. However, the most effective lubricants are difficult to apply and remove, and they add significantly to the cost. Efficient application of lubricants is particularly difficult in high-production operations where presses are being fed automatically. In such operations it is usually economical to use die metals that are more costly but more resistant to galling in combination with the usually less effective lubricants that can be applied automatically. Examples of these materials are aluminum bronzes, nitrided D2 tool steel and cemented carbides, which can be used for forming low-carbon steel with only mill-oil lubrication.

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Prevention of Galling

Table III lists chemical compositions of the die materials recommended in the selection tables. The die materials in Table IV with ratings of 90 to 100 are satisfactory in virtually all applications with only low-pressure lubricants such as ordinary mill oil. Materials in the range from 80 to 90 require excellent lubricants under conditions of severe galling and when scratches cannot be tolerated. If only moderate unit pressure is exerted by the dies, less effective lubricants can be used. Die materials rated below 80 usually require lubricants such as pigmented compounds, high-pressure oils or molybdenum disulfide if scratches cannot be tolerated. Attempting to stretch sheet metal beyond practical limits, poor tool fitting and rough finish on the surface of tools are common causes of galling. For short and medium runs surface-hardened hot rolled steel dies will produce parts equal to those produced from most tool steel dies. Exceptions may be encountered in severe reductions or in forming metals that show a greater tendency to gall, such as austenitic stainless steel. However, tool steel dies may also gall under these conditions.

When galling is encountered, the tool fit and the thickness of the metal being formed should be checked first to determine whether clearance is adequate. Attempts to iron out wrinkles will often cause galling. Whenever possible, wrinkles should be prevented by the design of the tools.

Nitriding minimizes or prevents galling of dies made from alloy steel or alloy tool steel such as type A2 or D2. It is not recommended for steels that contain no nitride-forming elements such as chromium or molybdenum. Nitrided surfaces on such steel may spall off on radii smaller than about ⅛ in., and plated surfaces on radii less than ¼ in., thus increasing the risk of failure in these locations.

Hard chromium plating will usually eliminate galling of mild steel, alloy steel and tool steel dies, and it is often used for severe duty. For operations involving high local pressures, hardened steels such as alloy or tool steels will be less likely to yield plastically and to cause cracking of the hard chromium plating.

Dirt, grit and shot fragments on the sheet cause greater damage to nitrided and chromium plated tools than to hardened tool steels; hard particles may cause minute spalling and small pits, especially at radii in areas of high forming pressure. When these pits in the die cause scratches on the formed sheet, the pits must be stoned out if high finish is required on the part. After such repairs have been made several times in the same area, the soft underlying metal will be exposed and renewal of the nitrided case or the chromium plate will be necessary.

Galling is less likely if the die materials and the metal being formed are dissimilar in hardness, chemical composition and surface characteristics. For instance, effective combinations are (1) aluminum bronze tools for forming carbon steel and stainless steel; (2) tool steel for forming aluminum and copper alloys; and (3) carbide tools for carbon steel, stainless steel and aluminum parts.

Tool Steels

Table V lists the tool steels recommended and rates them in regard to several important selection factors.

Water-hardening tool steels, not shown in the tables, are lowest in cost and best in machinability and weldability, but they often distort badly during heat treatment and have only fair resistance to galling and wear. They may be selected for moderate conditions such as the forming of aluminum with dies of a shape that would not be likely to distort seriously during heat treatment — for instance, the dies for making part 1 of aluminum. Carbon tool steel can be used in the annealed condition, hard faced with bronze or other wear-resistant material.

Steel O1 largely overcomes the heat treating problems encountered with water-hardening tool steel, and its machinability is almost as good. However, it is only slightly less costly than a more wear-resistant steel such as A2; its weldability is poor and it resists galling and wear little better than the water-hardening grades. Steel O1 is suitable for dies operating under moderate conditions and where distortion in heat treatment is a problem.

A2, only slightly more costly than O1, can be machined more easily than D2, distorts very little in heat treatment and has much greater resistance to wear and galling than O1. Furthermore, its resistance to wear and galling can be improved greatly by nitriding. Like O1 its welding properties are poor. It can be used for general insert applications for forming carbon steel and metals of similar strength.

D2 is more costly than A2 and less easily machined and welded but deforms very little in heat treatment. Its excellent resistance to galling and wear can be improved by nitriding as shown in Table V. D3 is similar to D2 but must be quenched in oil. These steels can be used as solid dies, as castings or as inserts for forming stainless steel and in severe applications.

The shock-resisting tool steels, particularly S1 (0.50% C, 1.50% Cr, 2.50% W), are useful primarily for die components that are fragile or subject to severe impact conditions. S1 has good machinability, distorts little in heat treatment and when carburized has good resistance to galling and wear.

High speed steels, such as M4 carburized, also can be used for forming dies and may be desirable in specific applications. However, these steels cost more than D2 or D3, and in most instances are no more desirable and are less widely available.

Table III. Nominal Compositions of Tool Materials Recommended in the Selection Tables on Pages 13 to 16

Material	Composition
Tool Steels	
O1, Oil-hardening, cold work	0.90% C; 1.00% Mn; 0.50 Cr; 0.50% Mo
A2, Air-hardening, medium alloy	1.00% C; 5.00% Cr; 1.00% Mo
D2, High-carbon high-chromium	1.50% C; 12.00% Cr; 1.00% Mo
Other Ferrous Alloys	
Hot rolled mild steel	Steels 1010 to 1018
Unalloyed cast iron, 185 to 225 Bhn	3% total C; 1.6% Si; 0.7% Mn (or equivalent)
Alloy cast iron, 200 to 250 Bhn	3% total C; 0.7% combined C; 1.6% Si; 0.4% Cr; 0.4% Mo (or equivalent)
Cast carbon steel, 185 to 225 Bhn	0.75% C
Cast alloy steel, 200 to 235 Bhn	0.45% C; 1.10% Cr; 0.40% Mo
4140 alloy steel	0.40% C; 0.60% Mn; 0.30% Si; 1% Cr; 0.20% Mo
Nonferrous Alloys	
Zinc alloy	4% Al; 3% Cu; 0.03% Mg; rem, Zn
Aluminum bronze, 270 to 300 Bhn	13% Al; 4% Fe; rem, Cu
Plastics	
Polyester-glass	50% polyester plastic; 50% glass in the form of cloth, strand or chopped fibers
Epoxy-glass	50% epoxy plastic; 50% glass as above
Polyester-metal	Polyester plastic reinforced with metal powder
Epoxy-metal	Epoxy plastic reinforced with metal powder
Nylon-metal	Polyamide plastic reinforced with metal powder
Polyester or epoxy-glass-metal	Polyester or epoxy plastic with both glass and metal as above

Table IV. Relative Ratings of Die Materials for Resistance to Galling
(Materials are listed in order of decreasing wear resistance)

Die Material	Relative Resistance to Galling in Forming — Carbon Steel	Stainless Steel	Aluminum
D2 or D3 tool steel (nitrided)	95	90	100
A2 tool steel (nitrided)	90	80	100
Hard chromium plating	100	95	100
D3 tool steel	80	70	100
D2 tool steel	75	65	100
A2 tool steel	70	60	100
O1 tool steel	65	55	100
Hot rolled mild steel (carburized)	60	50	100
4140 alloy steel (flame hardened)	55	45	100
Cast iron (hardened)	80	70	100
Aluminum bronze (270 to 300 Bhn)	100	100	100
Cast iron (unhardened)	75	65	100
Hot rolled mild steel (as rolled)	20	10	90
Zinc alloy	100	100	100
Plastic-glass	100	100	100

Table V. Approximate Ratings of Selection Factors for Tool Steels Shown in Previous Tables

AISI-SAE	Approximate Cost per Lb[a]	Resistance to Wear[b]	Resistance to Galling	Relative Toughness	Relative Machinability[c]
Oil Hardening Tool Steels					
O1	$0.50	10	65	10	90
D3	0.80	60	80	4	40
D3 (nitrided)	...	100	95	..	..
Air Hardening Tool Steels					
A2	0.55	30	70	8	65
A2 (nitrided)	...	90	90	..	..
D2	0.80	50	75	6	45
D2 (nitrided)	...	100	95	..	..

(a) Cost varies with size and quantity. Figures given represent base price plus annealing and warehouse extras, and do not include extras for size, quantity, cutting or delivery. (b) According to the ratings given, a steel rated 50 will produce 10 times as many parts as one rated 5 with the same amount of wear. (c) The machinability of D2, D3 and A2 can be almost doubled by the addition of sulfur in the wrought forms.

Cast Iron

Cast iron is a useful die material for forming parts larger than about 12 in. as shown in Table I. Its performance makes it suitable for use in medium production runs or in short runs of large parts. When cast iron is used with inserts, it will produce greater quantities, as shown by the tables on pages 14 to 17.

Both types of cast iron listed in Table III should have predominantly fine pearlite with no massive carbides and a minimum of ferrite. Graphite should be of AFS-ASTM type A distribution (shown on page 23 in the article on Gray Iron in this Supplement) with a preferred flake size of 4 to 5.

Alloy cast iron should be flame hardenable to the equivalent of 450 Bhn with air cooling. The alloy iron given in Table III is sufficiently hardenable for oil quenching of small dies and local flame hardening with air cooling for dies too large to be quenched. When no heat treating is anticipated, the unalloyed iron is usually preferable because of lower cost and better machinability. However, alloy iron will usually wear less, even without flame hardening or other heat treatment.

Zinc Alloy

Zinc alloy has high pattern fidelity when cast but requires very accurate shrink patterns to minimize hand labor in finishing. Zinc alloy is economical only for die components at least 12 in. long, and it is most economical in dies about 36 in. long, as is evident in the selection tables on pages 14 to 17. One of the principal values of zinc alloy is for complicated dies that would require intricate machining and hand tooling if made of cast iron, but which can be cast more closely to shape in zinc alloy. In tensile strength, compressive strength and hardness, zinc tool alloys are inferior to other metals used in die construction.

If compound curves on the face of a stamping have no sharp creases or embossments with sharp corners, it is not unusual for zinc alloy dies to give the length of service indicated on page 14. Zinc alloy tools are particularly sensitive to surface roughness, thickness and hardness of the sheet metal being formed. The increase of any one of these multiplies unit pressures over a small area of the die face.

In production use, zinc alloy drawing dies in double-action presses have been found to give the longest life. Contrary to conventional diemaking practice, zinc alloy dies, being cast to shape, are made of as few components as possible. This not only results in a lower cost because fasteners are largely eliminated, but it adds to the simplicity and durability of the tool. Otherwise zinc alloy tools for conventional press production are designed according to the usual practice.

Virtually all of the zinc alloy in a

tool can be salvaged for reuse simply by melting. For greatest economy, the user must have melting and molding facilities available; the commercial scrap value of the alloy is about 65% of the original cost, while remelting costs the user about as much as melting purchased metal. These facilities, plus the necessary auxiliaries, cost a minimum of $50,000 to install.

Cycle time or press speed has a great effect on the life of zinc alloy tools. A die component moving more than 25 in. per min during its working cycle is highly destructive to zinc alloy. The best results have been obtained on double-action presses that average 3 strokes per min and involve drawing to a depth of above 6 in. For this work hydraulic presses are more desirable than mechanical presses. Therefore tools made from zinc alloys have a minimum size limit. This is true because even the slowest speed of small presses is greater than is permissible with zinc alloy tooling, and the cost is excessive if a small die is run on a large press merely to suit the speed requirements. Zinc alloy dies cannot be used with unlubricated stock because wear will be too rapid.

A zinc alloy containing 4% Al, 3.25% Cu, 0.1% Mg, 0.7% Ni and 0.2% Ti has been in general use in a few large plants for several years and has provided die life up to three times the periods indicated for the standard zinc alloy in the tables on pages 14 to 17.

Hot Rolled Mild Steel

Where a limited variety of tool materials are available, hot rolled mild steel plate with carbon content from 0.10 to 0.20% is in major use as a die material, and is also widely used elsewhere for short-run forming of small parts. This type of steel is not recommended without surface hardening. Dies are made by first torch cutting, then normalizing and grinding the stock. The dies are easily machined and generally are carburized, quenched and tempered after finish machining. No grinding should be done after carburizing. For a production quantity of 100,000 parts such as No. 5, the die is chromium-plated after hardening.

Hot rolled mild steel can be used for dies only where straightening facilities are available for correcting distortions induced by heat treatment. Straightening is necessary for all except symmetrical and thick shapes such as a large round punch.

4140 Alloy Steel

Because 4140 alloy steel is generally available in plate form and because it is hardenable by flame hardening, even with a hand torch, tooling for parts similar to No. 3 and 4 is comparatively simple. Such advantages exist only in relatively small flat dies.

The 4140 steel die to form part 3 is a simple five-element tool consisting of a punch, a die mounted to a pair of die shoes, and a spring or rubber-backed pad to eject the part from the lower die. A spring or rubber-backed stripper is used to strip the part from the upper punch. Steel 4140 would be selected for the punch and die because a component of this shape and size lends itself to low-cost design and toolmaking techniques. The punch and die can be cut from plate with a band saw so that only a small amount of filing and fitting is necessary. The edges of both the punch and die are then flame hardened, which eliminates furnace heat treatment. After grinding and polishing out the edges as necessary, the punch and die are fitted to mating die shoes and the pad and stripper are added, along with the necessary gages for locating the blanks.

When properly hardened and finished, such a die can produce 100,000 pieces or more. Some tools of this kind have produced more than 200,000 pieces from 0.060-in. cold rolled 1010 steel.

Cast Steel

Cast steel is used for forming parts larger than 12 in. long where the shape of the part makes a casting more feasible than wrought stock. Plain carbon steel (0.65 to 0.85% C) and alloy cast steel (0.40 to 0.50% C, 0.90 to 1.25% Mn, 0.90 to 1.25% Cr, 0.35 to 0.50% Mo) are two commonly used compositions. Cast steel is more costly and more difficult to machine than cast iron and shows a greater tendency to gall. However, it is tougher and more resistant to abrasive wear than cast iron. Both the alloy and plain carbon grades of cast steel can be flame hardened; the plain carbon grade must be water quenched whereas the alloy grade will harden in air.

One important advantage of cast steel, particularly the plain carbon grade, is its weldability. It can be rewelded with steel or hard surfaced with tool steels, aluminum bronzes and other hard surfacing materials. Because of its poorer resistance to galling it is less desirable for dies for forming carbon and stainless steels than for aluminum and copper alloys. Cast steel is also useful for restrike, flanging and other types of dies that are less likely to gall or pick up metal from the sheet.

Aluminum Bronzes

Aluminum bronzes, which are alloys principally of copper and aluminum, are available in a wide range of hardness from 120 to 340 Bhn. These alloys have excellent resistance to galling and are desirable for dies where best finish is required on carbon and stainless steel parts. The softer grades (120 to 270 Bhn) wear rapidly, particularly where wrinkling tends to occur on the formed part. The harder grades (270 to 340 Bhn) wear less rapidly but are difficult to machine, drill and tap. Where elimination of scratches is extremely important aluminum bronzes should be considered, but for medium to high production (10,000 to 100,000) replacement inserts should be available to permit reconditioning of worn tools.

Plastics

The raw materials used in plastics formulations are readily available, as are the prepared tool plastics. While satisfactory dies may be produced even in initial experiments with plastic material, the quality and economy improve greatly with experience.

Requiring no outlay for special equipment, plastic tooling may be produced on the usual toolmaking facilities. Patterns, prototype parts or models must be available for casting the resin (if no reinforcement is to be used) or for placing the resin-impregnated glass reinforcement on the face of dies that are built with reinforcement throughout. When a pattern of some kind is not available, there will be little or no cost advantage in using plastic rather than metal dies.

Such terms as nylon-metal, epoxy-metal, polyester-metal, which appear on pages 14 and 15, refer to plastics reinforced by the addition of metal powder to the uncured resin. The term "with inserts" in footnote e, pages 14 and 15, indicates that plastic dies selected to produce the quantities shown are reinforced at the areas of highest pressure and wear with inserts of tool steel, cast iron or alloy steel bolted or doweled in position in the die component.

The strength (10,000 to 40,000 psi) and, in particular, the hardness of plastics are inferior to those of metallic die materials. The problem of obtaining the required strength in a plastic die in some instances must be solved by extra work in designing or developing; but in many dies the regions of high pressure are confined to local areas, which, if anticipated, are strengthened with metallic inserts.

When plastic tooling is selected for a part that is subsequently changed in design, the necessary alterations of the tooling will be costly. In addition, if maintenance is required on a plastic die, the bonding of repair plastic to worn areas may be inadequate because of the previous absorption of oil by the plastic.

The cost of plastic per unit volume without reinforcing materials is from 1 to 2 times that of cast iron but less than that of primary zinc. However, unlike cast iron or zinc, it has no scrap value. The molding materials cost from 45 to 90¢ per lb and glass reinforcing materials cost as much as $1 per sq yd.

Except for very short runs, plastics should not be selected for blankholder material where burred edges of the blank slide over the plastic surface. Such areas will wear severely on plastic dies.

The Selection of Gray Cast Iron

By the ASM Committee on Gray Iron

THE GENERAL TERM "cast iron" includes gray iron, pig iron, white iron, chilled, malleable and nodular iron. This article deals only with gray iron.

The gray cast irons are alloys of iron, carbon and silicon in which more carbon is present than can be retained in solid solution in austenite at the eutectic temperature. The carbon in excess of austenite solubility in iron, precipitates as graphite flakes. The gray irons usually contain from 1.7 to 4.5% C and 1 to 3% Si.

Certain important but lower-volume specialty items in this family of cast metals, notably the austenitic and other highly alloyed irons, are not dealt with here; instead, emphasis is given to irons used in the largest amounts in the most applications.

Classes of Gray Iron. A simple and convenient classification of the gray irons is found in the ASTM specification A48, which relates the various types in terms of tensile strength. The ASTM classification by no means connotes a scale of ascending superiority from class 20 (min tensile strength, 20,000 psi) to class 60 (min tensile strength, 60,000 psi). In many applications strength is not the major criterion for the choice of grade. For example, in parts such as clutch plates and brake drums, where resistance to heat checking is important, the "lower" grades have performance advantages. Similarly, in heat-shock applications such as ingot or pig molds, a class 60 iron would fail quickly, whereas good performance is shown by class 25 iron. In machine tools and other parts subject to vibration, the better damping capacity of the lower-tensile irons may be advantageous.

Cost Considerations

Gray cast iron is the least expensive of all cast metals. The raw materials—pig iron, cast iron scrap, steel scrap, limestone, coke and air—are all relatively cheap. Operating costs for cupola melting units are also lower than for other types of furnaces.

Because gray iron is the least expensive type of casting, it should always be considered first when a cast metal is being selected. Another metal should be chosen only when the mechanical or physical properties of gray iron are inadequate.

The classic example of an application requiring a bare minimum of casting properties and lowest possible cost is a window sash weight. Gray iron weights are used in many types of industrial and consumer products, such as elevator counterweights, automatic clothes washer weights and industrial furnace door counterweights. Serving a similar purpose, gray iron is used for the bases of many types of machine tools and industrial equipment. In some of these the high damping capacity and wear resistance are also important.

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ASM-SLA CI

Gray iron is widely used also for guards and frames around hazardous machinery. Many types of gear housings, enclosures for electrical equipment, pump housings, and large housings, as for steam turbines, are usually cast in gray iron because of its low cost. Other similar gray iron castings are used for motor frames, motor bearing housings and fire hydrants.

Low cost is the decisive factor also in applications such as flatiron bases, fastener inserts in porcelain insulator bushings, valve housings, flanges, pulley sheaves, pipe fittings and other types of hardware. For lightly loaded gears and shafts, cost is the primary, but not the only, requirement. In many applications mechanical properties are unimportant because the section size selected automatically decreases the stress level to a low value.

Although the family of gray irons have many unique properties that may vary from one type to another, as discussed further in this article, it is nonetheless possible that, for a particular application, the engineer may safely specify *any* type of iron between class 30 and class 60. Selection then becomes a matter of cost analysis. Assuming that the casting design and wall section are compatible with both extremes, the economic aspects of such an application may be considered for a hypothetical 200-lb casting in both class 30 and class 60 irons.

Supersedes the article on page 505 of the 1948 ASM Metals Handbook

Factors that enter into the direct costs of a casting include melted metal, coremaking, molding, shakeout, cleaning and scrap loss. The manner in which these costs may be influenced by the type of iron is discussed below.

Cost of Melted Metal includes base charge, cost of conversion to molten metal, inoculants (generally used), alloy additions, if any, and melting loss. To determine the metal cost per unit weight of good castings, one more factor—yield—must be taken into consideration. Yield is generally expressed as the percentage of good castings weight obtained from the charged metal weight. With high yield there is less return metal to remelt, which in turn reduces the net cost of conversion, melting loss and inoculation. The ultimate metal cost of castings with a high yield is therefore less than that of low-yield castings.

The cost of the base charge for a class 30 iron is somewhat lower than for a class 60 metal. The class 30 iron is also cheaper to melt and requires only moderate inoculation with no alloying, whereas class 60 almost invariably must be alloyed to meet specifications consistently. Melting losses on both these irons are about the same, but because the class 60 iron has characteristically higher liquid shrinkage, it must be more heavily risered and therefore will have a lower yield.

A "fringe" cost item, seldom realized or appreciated by the consumer, pertains specifically to the alloyed irons (in this instance, the class 60 iron) with regard to the quantity ordered. If only a few tons or less of castings are required, it is generally unfeasible to attempt to recover the alloying elements in foundry returns (gates, risers and shop scrap) and hence the cost of the portion of alloy so diverted must be charged against the weight of good castings produced. In large tonnage melts of alloyed iron where there is a reasonable opportunity to segregate and use this alloyed iron scrap as such, the diverted alloy may be recovered, to the extent permitted by melting and oxidation losses, and thus will reduce the expenditure for alloying elements.

The cost of melted metal per good ton of a class 60 iron is about 2.3 times greater than that of a class 30 iron, when the alloy content of shop returns is unrecovered as such.

Coremaking Costs normally would not differ between class 30 and class 60 castings made to the same pattern.

Molding Cost with the same pattern for a class 60 casting may be substantially higher than for its counterpart in class 30 iron, because the liquid shrinkage of class 60 metal is about two to three times greater, and it is therefore necessary to incorporate larger feed risers to produce a casting free from voids caused by internal shrinkage. Use of larger feed risers, as located on the casting, in turn may necessitate use of a larger flask (mold) to contain them. As a result, the molding cost for the class 60 casting may be 1.2 to 1.6 times greater than for the same casting in class 30 metal. The great variety of casting designs will not permit establishing an absolute rule for differentials in molding cost, but the range given above is typical of many commercial castings.

Shakeout Costs are usually influenced by mold volume. If the class 60 casting requires a mold 1.2 to 1.6 times greater in volume than the mold required for the class 30 casting, the shakeout cost of the former may be as much as 20% more. In mechanized shakeout systems, the cost differential is relatively small for changes in mold volume.

Cleaning Costs. Because larger risers and riser pads were used in the class 60 casting, it follows that the cleaning cost will be higher than for the class 30 material. This could be about 1.1 times greater than for the class 30 casting.

Table I. Summary of Cost Factors for Casting in Example

Item	Class 30 Iron	Class 60 Iron
Coremaking	0.083	0.083
Molding	0.424	0.546
Shakeout	0.094	0.105
Cleaning	0.156	0.177
Scrap loss (control)	0.038	0.076
Total melted metal	0.205	0.474
	1.000	1.461

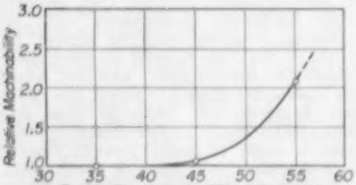

Fig. 1. Approximate Increase in Machining Costs with Increase in Tensile Strength of Gray Iron

Foundry Rejections. The general level of foundry rejections is usually reflected by the type of work in which the foundry is engaged. For example, the production shop that is turning out the same group of castings on a repetitive basis will have a lower scrap loss than the jobbing foundry that has hundreds of different patterns in varying quantities.

It is difficult to assess the relative scrap losses experienced with class 30 versus class 60 castings. For the foundry that is accustomed to producing class 60 iron and has established adequate control procedures, scrap losses in this type of metal would not be significantly higher than with the class 30 metal. On the other hand, a foundry that may do well with class 30 castings, but ventures into the high-tensile groups without suitable controls for these metals, may face staggering rejections because of shrinkage defects or failure to conform to physical specifications, or both. Control costs (such as testing, analytical work and technicians) are customarily carried in overhead charges and seldom appear as a direct cost item.

If any evaluation is to be given to the relative control costs (which determine the percentage of foundry rejections), it would be fair to say that class 60 iron castings require about twice the expenditure that is necessary for class 30 castings.

Machining Costs. While it is well known that the higher-tensile gray irons are not so readily machinable as the lower-tensile types, some consideration may be given to the feasibility of specifying the stronger type simply to improve the factor of safety. In the absence of any possibility of gaining improved wear resistance or response to heat treatment, it should be realized that "upgrading" a specification for a machined casting may entail additional machining costs, approximately in proportion to the factors shown in Fig. 1.

Total Cost. Omitting machining costs (for lack of more specific data), the comparative costs of making the hypothetical 200-lb casting in class 30 and class 60 irons may be summarized, as in Table I, by assigning to each item index numbers that reflect the cost factors relative to each other and that total to unity for the class 30 iron.

Under no circumstances should it be inferred that the comparison in Table I is valid for any casting other than the specific one selected for this comparison. The data presented are merely illustrative in a general way of some of the relative cost factors that may prevail in producing an identical shape in class 30 and also class 60 metal.

It should not be assumed that the cost spread between class 30 and class 60 irons is linear. Again using the hypothetical pattern, the chart shown in Fig. 2 illustrates typical cost relations for the gray iron series. These cost ratios are relative for each indicated item and are not additive as a whole.

In this chart, it will be noted that for gray irons with tensile strength less than 50,000 psi the principal variation is in the cost of metal. Metal cost is higher for the class 25 iron than for class 30 because of the necessity for high percentages of costly pig iron in the mix to achieve high total carbon levels in the class 25 castings.

Castability

Limitations attending successful production of a gray iron casting involve the interrelations among fluidity of the metal, section thicknesses in relation to each other in the casting, and section sensitivity as it may affect machinability. These factors may be condensed into a single term, "castability," which for gray iron may be defined as that measure of the metal which establishes the minimum section thickness that can be flowed into a mold cavity of given volume/area ratio to obtain physical properties consistent with the type of iron being poured.

Fluidity. Scrap losses resulting from misruns, cold shuts and round corners are often attributed to lack of fluidity of the metal poured.

Mold conditions, pouring speed and other process variables being equal, the fluidity of commercial gray irons depends primarily on the amount of superheating above the freezing temperature (liquidus). As the total carbon content decreases, the liquidus temperature increases, and the fluidity at a given pouring temperature therefore is decreased, as measured by the length of flow into a spiral-type fluidity test mold. This relation is shown in Fig. 3, which is similar to curves for other metals given in the article, "Fluidity

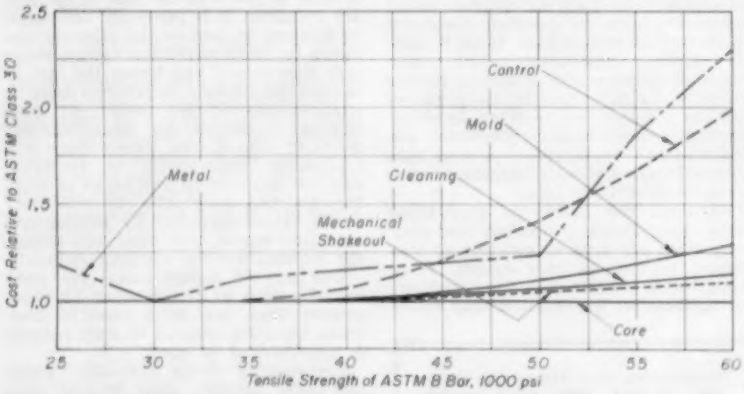

Fig. 2. Typical Cost Relations Among Various Types of Gray Iron Produced as Castings from the Same Pattern. Tensile strength class refers to results from ASTM "B" test specimens.

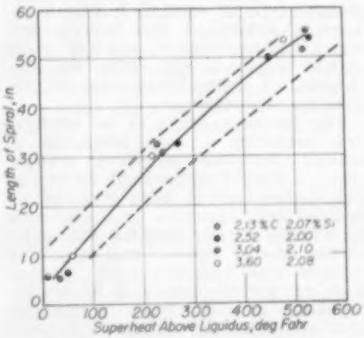

Fig. 3. Fluidity of Four Gray Irons of Different Carbon Content

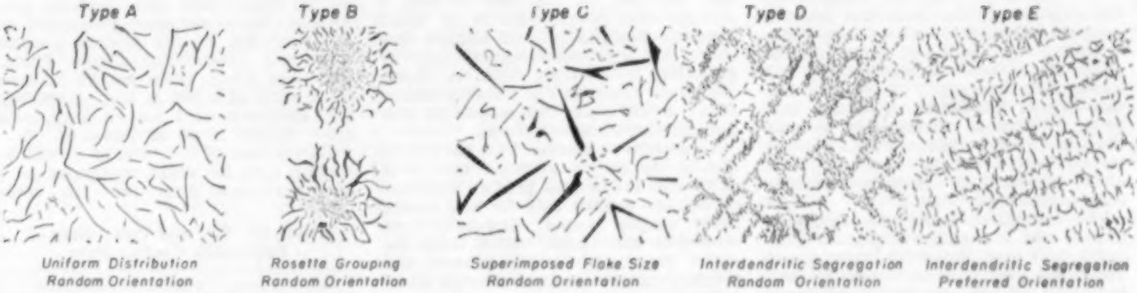

Fig. 4. Types of Graphite Flakes in Gray Iron (AFS-ASTM). In the recommended practice (ASTM A247) these charts are shown at a magnification of 100 diam. They have been reduced to one-third size for reproduction here.

of Metals", page 199 of the 1948 Metals Handbook.

Significance of the relations among fluidity, carbon content and pouring temperature becomes apparent when it is realized that the gradation in range of tensile strength in the ASTM classification of gray iron is achieved in large part by changing the carbon content of about 3.60 to 3.80% for class 20 to about 2.70 to 2.95% for class 60. The fluidity of these irons thus resolves into a measure of the practical limits of maximum pouring temperature as opposed to the liquidus of the iron being poured. These practical limits of maximum pouring temperature are determined largely by two factors: (1) the ability of both mold and cores to withstand the impact of molten iron, which ability decreases as the pouring temperature increases, thereby favoring low pouring temperatures; and (2) the fact that metal tap temperatures from a cupola seldom exceed 2800 to 2850 F, while tap temperatures from an electric arc furnace may be in the range from 2850 to 2900 F. Since ladling and reladling to the point of pouring generally accounts for temperature losses of 100 to 150 F, the final *maximum* pouring temperatures are about 2650 to 2700 F. Table II illustrates how the latitude between liquidus and pouring temperatures varies with carbon content.

Table II. Superheat for Irons of Various Carbon Contents Poured at 2650 F

Carbon, %	Liquidus, deg Fahr	Pouring Temperature, deg Fahr	Superheat Above Liquidus, deg Fahr
2.52	2360	2650	290
3.04	2270	2650	380
3.60	2150	2650	500

Data for 2% Si irons (W. S. Mott, R. H. Schaefer and Earnshaw Cook)

Section Sensitivity

In practice, the minimum thickness of section in which any given class of gray iron may be poured is more likely to depend on the cooling rate of the section than on the fluidity of the metal. For example, though a 12 by 12-in. plate ¼ in. thick can be poured in class 25 iron as well as in class 50, the latter casting would not be gray iron, because the cooling rate would be so rapid that massive carbides would be formed. Yet it is entirely feasible to cast a class 50 metal in a diesel engine cylinder head that has predominantly ¼-in. wall sections in the water jackets above the firing deck. This is simply because the cooling rate of the cylinder head has been reduced by the "mass effect" resulting from enclosed cores and the proximity (often less than ½ in.) of one ¼-in. wall to the other. Thus it is that the "geometry" of the casting has an important bearing on the selection of metal specification.

It should be recognized that by adjusting the silicon content or by the use of graphitizing additions (called "inoculants") in the ladle, the foundryman may decrease the section that can be cast gray and without massive carbides.

The mass effect associated with increasing thickness of section or decreasing rate of cooling is much more pronounced in gray iron than in cast steel, for instance. The mass effect in cast steel results in increased grain size in heavy sections. This also applies to gray iron but the most important effect is on graphite size and distribution, and the amount of carbon in the combined form.

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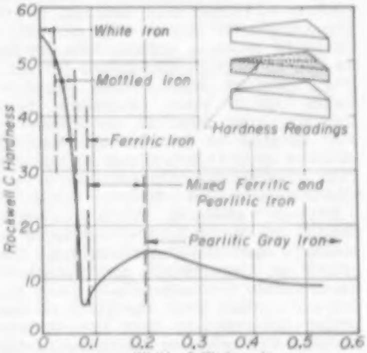

Fig. 5. Effect of Section Thickness on Hardness and Structure. Hardness readings at increasing distance from the tip of a cast wedge section, as shown by inset. Composition of iron: 3.52% C, 2.55% Si, 1.01% Mn, 0.215% P and 0.086% S. In most gray iron castings the structures are represented by the right-hand downward sloping portion of the curve beyond 0.2-in. wedge thickness. Thin sections may be represented by the left-hand downward portion. (R. Schneidewind and R. G. McElwee, Trans AFS, 58, 316, 1950)

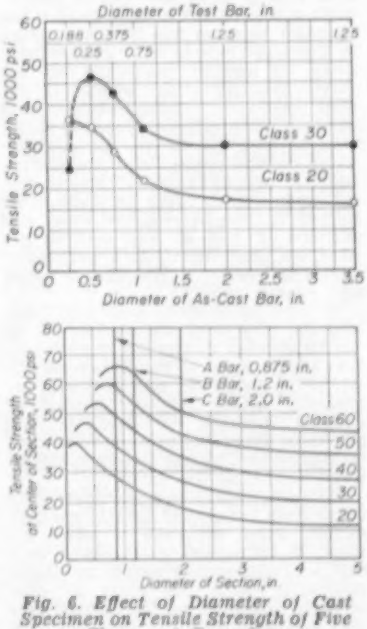

Fig. 6. Effect of Diameter of Cast Specimen on Tensile Strength of Five Classes of Gray Iron

For any given gray iron composition the rate of cooling from the freezing temperature to below about 1200 F determines the ratio of combined to graphitic carbon, which controls the hardness and strength of the iron. For this reason the effect of section size in gray iron is considerably greater than in the more homogeneous ferrous metals where cooling rate does not affect the form of the carbon content on a macroscopic scale.

The normal or usual microstructure of gray iron is a matrix of pearlite with graphite flakes dispersed throughout. Too rapid cooling (with respect to carbon and silicon contents) produces "mottled iron", consisting of a pearlitic matrix with both primary cementite (iron carbide) and graphite. Very slow cooling of irons that contain larger percentages of silicon and carbon is likely to produce considerable ferrite as well as pearlite throughout the matrix, together with coarse graphite flakes. Under some conditions, very fine graphite (type D, as shown in Fig. 4) may be formed near casting surfaces or in thin sections. Frequently such graphite is surrounded by a ferrite matrix; hence soft areas result.

Typical Variations. When a wedge-shaped bar with about 10-deg taper is cast in a sand mold, sectioned near the center of the length, and Rockwell hardness determinations are made on the cut surface from the point of the wedge progressively into the thicker sections, the curves so determined show to what extent continually increasing section size will affect the hardness, as shown in Fig. 5.

Progressing from the left of the curve in Fig. 5, the following metallographic constituents occur. The tip of the wedge is white iron (a mixture of carbide and pearlite) with hardness greater than Rockwell C 50. As the iron becomes mottled (a mixture of white iron and gray iron areas) the hardness decreases sharply. A minimum is reached because of the occurrence of fine type D graphite, which usually has associated with it large amounts of ferrite. With a slightly lower cooling rate, the structure becomes fine type A graphite in a pearlite matrix with the hardness rising to another maximum on the curve. This structure usually is the most desirable for wear resistance and strength. With increasing section thickness beyond this point, the graphite flakes become coarser and the pearlite lamellae are more widely spaced, resulting in slightly lower hardness. With further increase in wedge thickness and decrease in cooling rate, pearlite decomposes progressively to a mixture of ferrite and graphite, resulting in softer and weaker iron.

In most commercial gray iron castings the structures are represented by the right-hand downward sloping portion of the curve in Fig. 5, beyond 0.2-in. wedge thickness, and normally increasing section size is reflected by gradual lowering of hardness and strength. However, thin sections may be represented by the left-hand downward portion of the curve.

Figure 6 (top) shows average (of up to 10 tests per point) tensile strength of two irons, for each of which six sizes of cylindrical round bars were cast and appropriate tensile specimens machined. With the class 20 iron, strength increases as the as-cast section decreases down to the ¼-in. cast bar. However, for the class 30 iron, a section with ¼-in. diam is so small that the strength falls off sharply, because of the occurrence of type D graphite or mottled iron or both. The lower graph in Fig. 6 shows similar data for the same two classes of iron and for three higher classes.

Volume/Area Ratios. The variety of casting designs is so great that it is extremely difficult to predict with accuracy the cooling rate for any except fairly simple shapes. However, since *minimum* limitations, rather than the entire scope, are involved here, the problem can be resolved through comparisons of the casting design with ratios of volume to surface area or with minimum plate sections as generalized in practice.

The volume/area ratios (*V*/*A*) for round, square and plate sections provide a fairly accurate indication of the minimum casting sections possible in simple geometrical shapes (Table III). The 1.2-in. diam bar 21 in. long (*V*/*A* ratio of 0.290) is the ASTM "B" test specimen used for all gray irons from classes 20 to 60 inclusive.

Comparison of the ratio of volume to surface area for different shapes gives good agreement with the actual cool-

Table III. Volume/Area Ratios (V/A) for Round Bars, Square Bars and Plates [(a)]

Cast Form and Size	V/A
Bar, ½-in. diam by 21 in.	0.123
Bar, ½ in. sq by 21 in.	0.123
Plate, ¼ by 12 by 12 in.	0.120
Bar, 1.2-in. diam by 21 in.[(b)]	0.292
Bar, 1.2 in. sq by 21 in.	0.292
Plate, ⅝ by 12 by 12 in.	0.283
Bar, 2-in. diam by 22 in.	0.478
Bar, 2 in. sq by 22 in.	0.478
Plate, 1⅛ by 12 by 12 in.	0.474
Bar, 4-in. diam by 18 in.	0.900
Bar, 4 in. sq by 18 in.	0.900
Plate, 2 9/16 by 12 by 12 in.	0.898
Bar, 6-in. diam by 18 in.	1.286
Bar, 6 in. sq by 18 in.	1.286
Plate, 4½ by 12 by 12	1.286

(a) H. C. Winte, Trans AFS, 53, 436 (1946). (b) ASTM "B" test bar size.

Table IV. Bar and Plate Sizes of Equivalent Cooling Rate

Bar Diam, in.	Plate Thickness, in.	Ratio of Bar Diam to Plate Thickness
½	¼	2.0
1.2	⅝	1.92
2	1⅛	1.78
4	2 9/16	1.56
6	4½	1.33

For 12-in. square plates, as recorded in Table III.

Table V. Comparison of Tensile Strength of Gray Iron Castings and Test Bars

Ladle	Tensile Strength, psi Casting[(a)]	Tensile Strength, psi Test Bar[(b)]
1	30,150	32,050
2	31,150	33,550
3	32,650	32,200
4	35,100	36,300
5	37,000	37,800
6	39,400	34,200
7	42,300	39,100
8	45,400	42,600
	Avg difference = 2240 psi	

(a) Flat section from a 24-in. cross pipe fitting of nominal thickness 1.16 in. (b) Cylindrical test bar of 2-in. diam

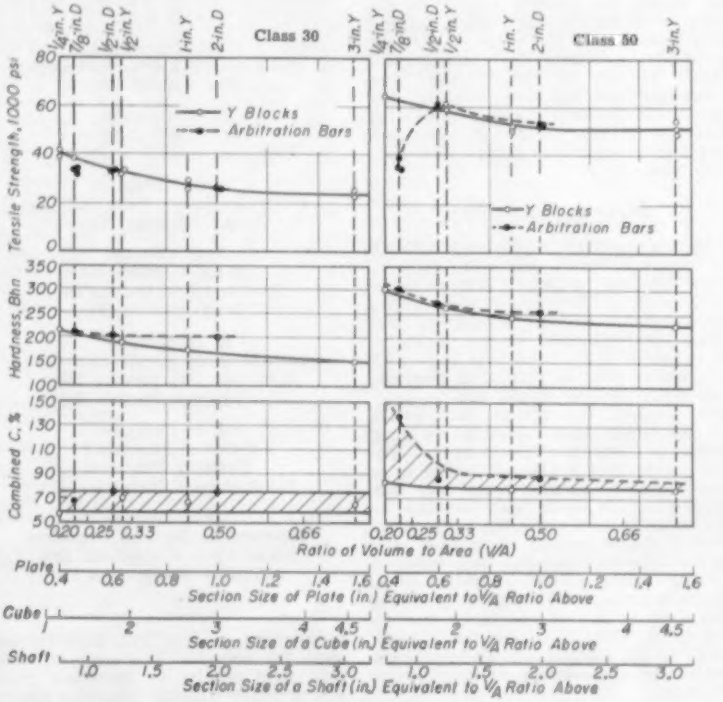

Fig. 7. Mechanical Properties of Class 30 and Class 50 Gray Iron. Composition of the class 30 iron: 3.40% C, 2.38% Si, 0.71% Mn, 0.423% P and 0.152% S; for the class 50 iron: 2.96% C, 1.63% Si, 1.05% Mn, 0.67% Mo, 0.114% P and 0.072% S (R. A. Flinn and R. W. Kraft, Trans AFS, 58, 153, 1950)

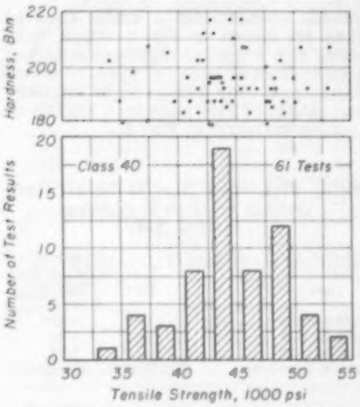

Fig. 8. Test Results for 61 Ladles of Class 40 Gray Iron. Measured on 0.505-in. test specimens

Table VI. Minimum Prevailing Casting Sections Recommended for Gray Irons

ASTM Class	Min, in.	V/A Ratio
20	⅛	0.061
25	¼	0.120
30	⅜	0.174
35	⅜	0.174
40	⅝	0.277
50	¾	0.326
60	1	0.416

V/A ratios are for square plates.

ing rates of castings made in the same mold material. For long round bars and infinite flat plates *V/A* is diameter/4 for bars and thickness/2 for plates; that is, a large plate casting would have the same cooling rate as a round bar with diameter twice the plate thickness. Most castings, however, freeze somewhat faster than an infinite flat plate, and instead of a 2 to 1 ratio of bar to plate, a smaller ratio often gives a better correlation with the cooling rate. The bar and plate sizes shown in Table IV are nearly equivalent in cooling rate.

Comparisons of the tensile strength of production castings with results from 2-in. diam test bars (Table V) confirm the calculations for plate castings versus round bars—specifically, line 3 of Table IV is confirmed. Other examples of this type of correlation are given in the paper cited in the footnote to Table III.

Relationships developed for various specific castings are valid when an iron of controlled composition, and therefore of similar section sensitivity, is used consistently. For instance, with copper-molybdenum iron of well controlled composition, tensile strength of 65,000 psi in the 1.20-in. diam test specimen has been found to assure 50,000 psi tensile strength in a cast crankshaft 7 ft long with sections thicker than 1.2 in. Such translation of properties of a small test bar to properties expected in a larger section cannot be done indiscriminately, because different irons may vary widely in section sensitivity.

Prevailing Sections

Although the ASTM "B" test bar (1.2-in. diam) is used for all gray irons from classes 20 to 60 inclusive, in practice it is customary to be somewhat more definite regarding minimum *prevailing* casting sections feasible for the various ASTM types of cast iron. As summarized in Table VI, these minimum prevailing sections include the requirement for freedom from carbidic areas. In a platelike section, occasional thinner walls (such as ribs) are of no importance unless they are ridiculously thin or appended to the outer edges of the casting.

Physical properties of class 30 and class 50 gray irons in various sections are shown in Fig. 7. For the class 30 iron, the combined carbon content and hardness are still at a safe level in sections equivalent to a 0.4-in. plate, which has *V/A* ratio of about 0.20. For the class 50 iron, however, both the combined carbon and Brinell hardness show a marked increase when the equivalent plate section is decreased to about 0.6 in. thick, with *V/A* ratio around 0.27. These results are consistent with the minimum prevailing casting sections recommended in Table VI.

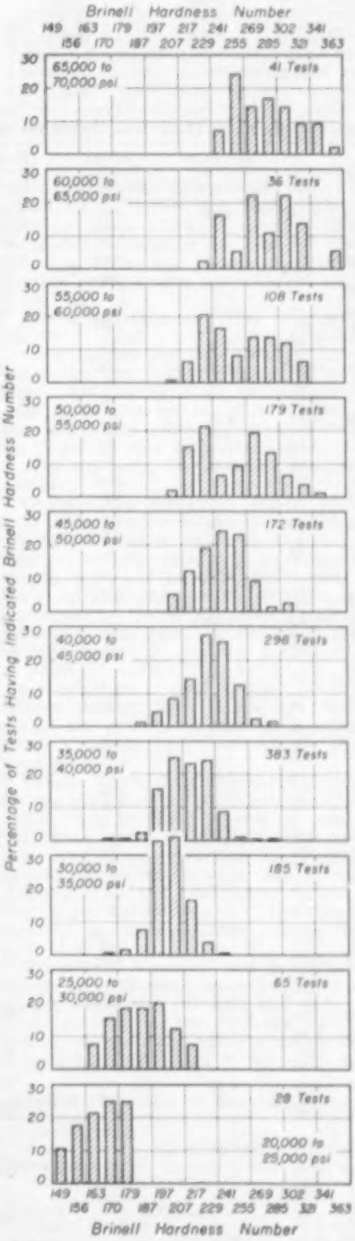

Fig. 9. Distribution of Hardness Test Results on Gray Iron for Various Ranges of Tensile Strength. Replotted from data of J. T. Mackenzie, Proc ASTM, 46, 1025, 1946

The hazards involved in pouring a given class of gray iron in a plate section thinner than recommended are discovered when the casting is machined. Typical losses in the machine shop as a result of improper specification are shown in the following example of "hard spot" rejection rate for castings of prevailing section ⅜ in.:

Class 35	Rejections negligible
Class 45	15 to 25% rejections
Class 55	80 to 100% rejections

In marginal applications a higher test specification may sometimes be used by decreasing the cooling rate of the casting (and thus, in effect, increasing the section thickness) by judicious placement of flow-offs and risers. An example is the successful production of a 1-in. diam single-throw crankshaft for an air compressor. This shaft was hard at the extreme ends when poured in class 50 iron. The difficulty was corrected by flowing metal through each end into flow-off risers that adequately balanced the cooling rate at the ends with the center portion of the casting.

In summation, the selection of a suitable grade of gray iron for a specific casting will necessarily require an evaluation of the size and shape of the casting as related to its cooling rate, or volume/area ratio. For a majority of parts, this evaluation need be no more than a determination of whether or not the *V/A* ratio of the casting exceeds the minimum *V/A* ratio indicated for the grade being considered (Table VI).

Test Bar Properties

Mechanical property values obtained from test bars are sometimes the only available guide to the actual mechanical properties of the metal in production castings. When test bars and castings are both poured from the same metal and the subsequent thermal histories are nearly identical, the strength of test bars does give a general indication of the strength of the metal in the castings. However, test bar results cannot be assumed to represent accurately the properties of each cubic inch of metal in the castings.

Usual Tests. Tension and transverse tests on bars cast for these purposes are the most common for evaluating the strength of gray iron.

Yield strength, elongation and reduction of area are seldom determined in the standard tension test of cast iron. The transverse test measures strength in bending and has the additional advantage that a deflection value may be obtained readily (see articles on pages 125 and 136 of the 1948 Metals Handbook). Minimum specification values are given in Table VII. Data usually can be obtained faster from the transverse test than from the tension test because machining of the specimen is unnecessary. Also, centerline shrinkage, which may occur in the usual cylindrical test bar, does not affect the transverse test significantly. The surface condition of the bar will affect the transverse test but not the tension test made on a machined specimen.

Hardness tests, on either test bars or castings, are used as an approximate measure of strength and sometimes as an inverse indication of machinability. Relations between Brinell hardness and tensile strength for a single class of iron are shown in Fig. 8, which indicates also a typical distribution of test results from 61 ladles of metal intended for class 40 gray iron castings. Statistical results of 1495 tests on a variety of irons are shown in Fig. 9.

Table VII. Minimum Transverse Breaking Loads (ASTM A48)

ASTM Class	Minimum Tensile Strength, psi	Minimum Transverse Breaking Load, lb — 0.875-In. Diam 12-In. Supports	1.2-In. Diam 18-In. Supports	2.0-In. Diam 24-In. Supports
20	20,000	900	1,800	6,000
25	25,000	1,025	2,000	6,800
30	30,000	1,150	2,200	7,600
35	35,000	1,275	2,400	8,300
40	40,000	1,400	2,600	9,100
50	50,000	1,675	3,000	10,300
60	60,000	1,925	3,400	12,500

For separately cast test specimens. Included in specifications only by agreement between manufacturer and purchaser

Table VIII. Test Bars to Match Controlling Sections of Castings (ASTM A48)

Controlling Section, in.	Test Bar	Diameter of As-Cast Test Bar, in.
0.50 and less	A	0.875
0.51 to 1.00	B	1.20
1.01 to 2.00	C	2.00
More than 2.00	Bar C or by agreement	

Table IX. Typical Compositions of Gray Iron Based on Strength and Section

Type	Composition, % — TC	Si	P	S	Mn	Average Carbon Equivalent[(a)]	Metal Section Range, in.	Brinell Hardness Number	Transverse Load, lb	Transverse Deflection, in.	Tensile Strength, psi
Class 20	3.50	2.40	0.20	0.08	0.50	4.56	Up	166	900	0.10	22,000
Light section	to	to	to	to	to	...	to	to	to	to	to
0.875-in. test bar	3.80	2.60	0.80	0.13	0.70	...	0.50	200	1200	0.15	26,000
Class 20	3.40	2.30	0.20	0.08	...	4.34	½	160	1600	0.20	18,000
Medium section	to	to	to	to	...	...	to	to	to	to	to
1.2-in. test bar	3.60	2.50	0.60	0.80	...	...	1	180	2200	0.27	24,000
Class 20	3.10	2.20	0.20	0.08	0.50	3.98	1	130	4500	...	18,000
Heavy section	to	to	to	to	to	...	and	to	to	...	to
2.0-in. test bar	3.30	2.40	0.40	0.13	0.80	...	up	180	6500	...	22,000
Class 25	3.30	2.20	0.20	0.08	0.50	4.20	Up	160	950	0.11	26,000
Light section	to	to	to	to	to	...	to	to	to	to	to
0.875-in. test bar	3.50	2.40	0.50	0.13	0.80	...	½	180	1300	0.16	29,000
Class 25	3.20	2.20	0.15	0.08	0.50	4.08	½	172	1800	0.22	26,000
Medium section	to	to	to	to	to	...	to	to	to	to	to
1.2-in. test bar	3.40	2.40	0.40	0.12	0.80	...	1	207	2400	0.28	29,000
Class 25	3.00	1.90	0.15	0.08	0.50	3.82	1	179	6000	...	26,000
Heavy section	to	to	to	to	to	...	and	to	to	...	to
2.0-in. test bar	3.30	2.20	0.25	0.12	0.80	...	up	217	7800	...	30,000
Class 30	3.20	2.10	0.15	0.08	0.50	4.03	½	179	1250	...	30,000
Light section	to	to	to	to	to	...	to	to	to	...	to
0.875-in. test bar	3.40	2.30	0.30	0.12	0.80	...	1	228	1500	...	34,500
Class 30	3.10	2.10	0.15	...	...	3.92	...	...	...	...	.....
Medium section	to	to	to	...	...	...	...	...	...	...	.....
1.2-in. test bar	3.30	2.30	0.25	...	...	...	...	...	...	...	.....
Class 30	2.90	1.70	0.15	0.08	0.45	3.68	1	207	6500	...	30,000
Heavy section	to	to	to	to	to	...	and	to	to	...	to
2.0-in. test bar	3.20	2.10	0.25	0.12	0.70	...	up	228	8200	...	34,500
Class 35	3.10	2.00	0.15	0.08	0.45	3.90	...	179	1150	...	36,000
Light section	to	to	to	to	to	...	to	to	to	...	to
0.875-in. test bar	3.30	2.20	0.20	0.12	0.70	...	½	228	1450	...	40,000
Class 35	3.00	1.80	0.15	0.07	0.46	3.77	½	207	2300	0.25	35,000
Medium section	to	to	to	to	to	...	to	to	to	to	to
1.2-in. test bar	3.25	2.10	0.25	0.12	0.70	...	1	228	3000	0.35	39,000
Class 35	2.80	1.60	0.10	0.06	0.45	3.54	1	183	7500	0.32	35,000
Heavy section	to	to	to	to	to	...	and	to	to	to	to
2.0-in. test bar	3.10	2.00	0.20	0.12	0.70	...	up	217	9000	0.38	38,000
Class 40	3.00	1.90	0.10	0.07	0.45	3.77	...	212	1275	...	42,000
Light section	to	to	to	to	to	...	to	to	to	...	to
0.875-in. test bar	3.20	2.20	0.25	0.12	0.65	...	½	241	1550	...	46,000
Class 40	2.95	1.70	0.10	0.06	0.45	3.65	½	207	2500	0.25	40,000
Medium section	to	to	to	to	to	...	to	to	to	to	to
1.2-in. test bar	3.15	2.00	0.20	0.11	0.70	...	1	241	3400	0.35	47,000
Class 40	2.75	1.50	0.07	0.05	0.50	3.42	1	180	8400	0.30	41,000
Heavy section	to	to	to	to	to	...	and	to	to	to	to
2.0-in. test bar	3.00	1.90	0.15	0.12	0.70	...	up	217	9600	0.38	45,000
Class 50	2.90	1.70	0.10	0.06	0.50	3.62	...	226	1600	...	51,000
Light section	to	to	to	to	to	...	to	to	to	...	to
0.875-in. test bar	3.10	2.10	0.20	0.12	0.70	...	½	269	1800	...	55,000
Class 50	2.70	1.70	0.10	0.06	0.60	3.45	½	228	3000	0.28	50,000
Medium section	to	to	to	to	to	...	to	to	to	to	to
1.2-in. test bar	3.00	2.00	0.20	0.11	0.80	...	1	269	4000	0.34	57,000
Class 50	2.55	1.40	0.07	0.06	0.60	3.20	1	207	10,000	0.38	50,000
Heavy section	to	to	to	to	to	...	and	to	to	to	to
2.0-in. test bar	2.85	1.70	0.15	0.11	0.80	...	up	241	12,500	0.48	54,000
Class 60	2.70	1.90	0.10	0.06	0.50	3.51	...	220	1750	...	60,000
Light section	to	to	to	to	to	...	...	to	to	...	to
0.875-in. test bar	3.00	2.20	0.20	0.12	0.70	...	...	272	2000	...	65,000
Class 60	2.50	1.90	0.05	0.05	0.70	3.37	...	248	3400	0.25	60,000
Medium section	to	to	to	to	to	...	...	to	to	to	to
1.2-in. test bar	2.85	2.10	0.15	0.10	1.00	...	...	290	4500	0.40	65,000
Class 60	2.50	1.20	0.07	0.05	0.50	3.09	...	212	11,500	0.35	60,000
Heavy section	to	to	to	to	to	...	...	to	to	to	to
2.0-in. test bar	2.80	1.50	0.15	0.12	0.80	...	...	248	13,500	0.50	64,000

(a) "Carbon equivalent" is calculated as percentage carbon plus 0.3 times the sum of percentage silicon and phosphorus. Some use carbon plus 1/3 silicon. Data in this table from "Handbook of Cupola Operation", AFS, 1946.

Table X. Mechanical Properties of Automotive-Type Gray Iron

SAE No.	Brinell Hardness Number	Minimum Transverse Load, lb	Minimum Deflection, in.	Minimum Tensile Strength, psi
110	187 max	1800	0.15	20,000
111	170 to 223	2200	0.20	30,000
120	187 to 241	2400	0.24	35,000
121	202 to 255	2600	0.27	40,000
122	217 to 269	2800	0.30	45,000

SAE Handbook, 1955, page 180. Properties determined from arbitration test bar (1.2-in. diam) as cast or stress relieved at 1050 F max

Table XI. Typical Base Compositions of Automotive-Type Gray Iron

SAE No.	TC	Si	P	S	Mn
110	3.40 to 3.70	2.80 to 2.30	0.25	0.15	0.50 to 0.80
111	3.25 to 3.50	2.30 to 2.00	0.20	0.15	0.60 to 0.90
120	3.20 to 3.40	2.20 to 1.90	0.15	0.15	0.60 to 0.90
121	3.10 to 3.30	2.10 to 1.80	0.12	0.15	0.60 to 0.90
122	3.00 to 3.20	2.10 to 1.80	0.10	0.15	0.70 to 1.00

SAE Handbook, 1955, page 181. See Table X for mechanical properties. If either carbon or silicon is on the high side of the range, the other should be on the low side.

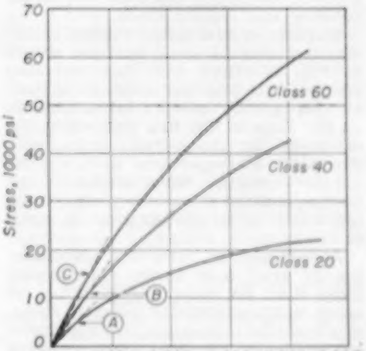

Fig. 10. Typical Stress-Strain Curves for Three Classes of Gray Iron in Tension. Modulus of elasticity is measured to points A, B and C, representing ¼ of the tensile strength.

Typical Specifications. ASTM A48 is typical of specifications based on test bars: three sizes of separately cast cylindrical specimens are used to match, approximately, the controlling section of a casting with one of the standard test bar sections. After manufacturer and purchaser agree on a controlling section of the casting, the corresponding test bar is specified by the designations given in Table VIII.

Most engineering castings in gray iron are specified as either class 25, 30 or 35. Specification A48 is based entirely on mechanical properties, and the composition to give the required properties can be selected by the individual producer. A manufacturer whose major production is, for instance, medium-section castings of class 35 iron will find, for castings of heavy section where the 2-in. test bar is required for qualifying, that the same metal will not meet the requirements for class 35. It will qualify only for some lower class, such as 25 or 30. As thickness of the controlling section increases, the composition must be adjusted to maintain the same tensile strength in the heavier sections.

Table IX gives typical compositions to meet the various classes of ASTM A48. The values in this table are only suggestions and not a part of the specifications, but they have been computed carefully and checked against successful practice. It will be noted that increased strength is obtained by progressively lowering the carbon and silicon contents.

The SAE standard on automotive gray iron castings (Tables X and XI) exemplifies a set of requirements more specific than ASTM A48. Only one size of test bar is used (1.2-in. diam); an iron intended for heavy sections, such as SAE 122, is specified to have higher strength and hardness in the same standard test bar as used for SAE 111, which is intended for light-section castings. Many European specifications for gray iron castings are based on the use of a single size of specimen with varying requirements for different sections.

ASTM specifications other than A48 include: A159 (automotive), A126 (valves, flanges and pipe fittings), A74 (soil pipe and fittings), A142 (culvert pipe), A44 (water pipe), A190 (lightweight and thin sections), A278 (pressure-containing parts for temperatures up to 650 F) and A319 (non-pressure-containing parts for elevated temperatures).

Compressive Strength. When gray iron is used for structure and machinery foundations or supports, the engineer is usually designing to support weight only, and he bases his calculations on the compressive strength of the material. Table XII, giving typical values for mechanical properties of the various grades, shows the high compressive strength of gray irons. If loads other than dead weights are involved (unless these loads are constant) the problem is one of dynamic stresses, which are discussed on the next page.

Tensile Strength is considered in selecting gray iron for parts intended for static loads in direct tension or bending. Such parts include pressure vessels, autoclaves, housings and other enclosures, valves, fittings and levers. Depending on the uncertainty of loading, safety factors of 2 to 12 have been used in figuring allowable stresses for such designs.

Transverse Strength and Deflection. When an arbitration bar is loaded as a simple beam and the load and deflection required to break it are determined, the resulting value is converted into a nominal index of strength by using the standard beam formula. The value so determined is arbitrarily called the "modulus of rupture". The values for modulus of rupture are useful for production control, but cannot be used in the design of castings without further analysis and interpretation. Rarely does a casting have a shape such that those areas subject to bending stress have a direct relationship to the round arbitration bar. A more rational approach is to use the tensile strength (or fatigue limit) and, after determining the section modulus of the actual shape, to apply the proper bending formula. However, because of the difficulty in obtaining a meaningful value for the tensile strength in tests of small specimens, the load computed in this manner will usually be somewhat lower than the actual load required to rupture the part, unless unfavorable residual stresses are present in the finished part.

Elongation of gray iron at fracture is very small (of the order of 0.006 in. per in.) and hence is seldom reported. The designer cannot use the numerical value of permanent elongation in any quantitative manner.

Torsional Shear Strength. As shown in Table XII, most gray irons have high torsional shear strength. Many grades have torsional strength greater than some grades of steel. This characteristic along with low notch sensitivity makes gray iron a suitable material for shafting of various types, particularly in the grades of higher tensile strength. Most shafts are subjected to dynamic torsional stresses and the designer should consider carefully the exact nature of the loads. For the higher-strength irons, stress concentration factors associated with changes of shape in the part are im-

Table XII. Typical Mechanical Properties of Standard Gray Iron Test Bars, As Cast

ASTM Class	Tensile Strength, psi	Compressive Strength, psi	Torsional Shear Strength, psi	Modulus of Elasticity, million psi: Tension	Modulus of Elasticity, million psi: Torsion	Reversed Bending Fatigue Limit, psi	Transverse Strength of 1.2-In. Diam Bar, 18-In. Span, lb	Brinell Hardness Number
20	22,000	83,000	26,000	9.6 to 14.0	3.9 to 5.6	10,000	1850	156
25	26,000	97,000	32,000	11.5 to 14.8	4.6 to 6.0	11,500	2175	174
30	31,000	109,000	40,000	13.0 to 16.4	5.2 to 6.6	14,000	2525	201
35	36,500	124,000	48,500	14.5 to 17.2	5.8 to 6.9	16,000	2850	212
40	42,500	140,000	57,000	16.0 to 20.0	6.4 to 7.8	18,500	3175	235
50	52,500	164,000	73,000	18.8 to 22.8	7.2 to 8.0	21,500	3600	262
60	62,500	187,500	88,500	20.4 to 23.5	7.8 to 8.5	24,500	3700	302

portant for torque loads as well as for bending and tension loads.

Modulus of Elasticity. Typical stress-strain curves for gray iron are shown in Fig. 10. Gray iron does not obey Hooke's law and the modulus in tension is usually determined arbitrarily as the slope of the line connecting the origin of the stress-strain curve with the point corresponding to ¼ of the tensile strength. Some engineers use the slope of the stress-strain curve near the origin for determining the modulus of elasticity.

As indicated in Table XII, the modulus of gray iron varies considerably more than for most metals. Thus, in using observed strain to calculate stress, it is essential to measure the modulus of the particular gray iron specimen being considered. The numerical value of the modulus in torsion is always less than in tension, just as it is for steel.

Hardness of gray iron, as measured by Brinell or Rockwell testers, is an average result of the soft graphite in the iron and the metallic matrix. Variations in graphite size and distribution will cause wide variations in hardness (particularly Rockwell hardness) even though the hardness of the metallic matrix is constant. To illustrate this effect, the microhardness of the matrix of five types of hardened iron, as compared with Rockwell C measurements on the same iron, is shown in Table XIII.

It is apparent that if any hardness correlation is to be attempted, the graphite must be constant as to type and amount in the irons being compared. It is recommended that Brinell hardness be used wherever possible.

Fatigue Limit in Reversed Bending

Because fatigue limits are expensive to determine, the designer usually has incomplete information on this property. Typical S-N curves for gray iron under completely reversed cycles of bending stress are shown in the graph on left in Fig. 11, in which each point represents the data from one specimen. The effects of temperature on fatigue limit and tensile strength are shown in the right-hand graph in Fig. 11.

Axial loading or torsional loading cycles are frequently encountered in designing parts of cast iron, and in many instances these are not completely reversed loads. Types of regularly repeated stress variation usually can be expressed as a function of a mean stress and a stress range. Wherever possible the designer should use actual data from the limited information available. Without precisely applicable test data, an estimate of the reversed bending fatigue limit of machined parts may be made by using about 35% of the minimum specified tensile strength of the particular grade of gray iron being considered. This is probably a safe value rather than an average of the few data available concerning the fatigue limit for gray iron.

An approximation of the effect of range of stress on the fatigue limit may be obtained from diagrams such as Fig. 12. The tensile strength is plotted on the horizontal axis to represent the fracture strength under static load (which corresponds to zero stress range). The reversed bending fatigue limit value is plotted on the ordinate for zero mean stress, and the two points are joined by a straight line. The resulting diagram is a chart for the fatigue limit (maximum value of alternating stress) for all values of mean stress.

Few data available are applicable to a design problem involving dynamic loading where the stress cycle is predominantly compressive, rather than tensile. Some work done on aluminum and steel indicates that for compressive (negative) mean stress, the behavior of these materials could be represented by a horizontal line beginning at the fatigue limit in reversed bending as indicated in Fig. 12. Gray iron is probably at least as strong as this for loading cycles resulting in negative mean stress, since it is much stronger in static compression than in static tension. It is therefore a natural assumption that the parallel behavior as illustrated in Fig. 12 is conservative.

If the designer has confidence that the real stress cycle is known, and he has enough data available for a reliable S-N diagram for the gray iron proposed, he might dimension the casting to obtain a minimum factor of safety of 2 in fatigue. Some uses may indicate greater conservatism or more liberal loading. The approximate safety factor is best illustrated by point *P* in Fig. 12. The safety factor is determined by the distance from the origin to the fatigue limit line along a ray through the cyclic stress point, divided by the distance from the origin to that point. In Fig. 12 this is *OF/OP*.

On this diagram, point *P′* represents

Table XIII. Comparison of Rockwell Hardness of Gray Irons, as Influenced by Graphite

Type of Graphite	Total Carbon, %	Rockwell C Hardness[a]	Matrix Converted[b]
A	3.06	45.2[c]	61.5
A	3.53	43.1	61.0
A	4.00	32.0	62.0
D	3.30	54.0	62.5
D	3.60	48.7	60.5

(a) Measured by conventional Rockwell C test. (b) Hardness of matrix, measured with superficial hardness tester and converted to Rockwell C. (c) Although this value was obtained in the specific test cited, it is not typical of gray iron of 3.06% C. Ordinarily the hardness of such iron is Rockwell C 48 to 50.

a stress cycle having a negative mean stress. In other words, the maximum compressive stress is greater than the tensile stress reached during the loading cycle. In this instance, the safety factor is the distance *OF′/OP′*. However, this analysis assumes that overloads will increase the mean stress and alternating stress in the same proportion. This may not always be true, particularly in systems with mechanical vibration where the mean stress may remain constant. For this condition the vertical line through P would be used; that is, DK/DP would be the factor of safety.

Most engineers use diagrams such as Fig. 12 mainly to determine whether a given condition of mean stress and cyclical stress results in a design safe for infinite life. The designer can also determine whether variations in the mean stress and the alternating stress that he anticipates will place his design in the unsafe zone. Usually the data required to analyze a particular set of conditions are obtained experimentally. It is emphasized that the cycles of alternating stress implied in Fig. 12 are those used to determine fatigue limits—approximately 10 million. Fewer cycles, as encountered in infrequent overloads, will be safer than indicated by a particular point plotted on a diagram for infinite life. Insufficient data are available to draw a diagram for less than infinite life.

Fatigue Notch Sensitivity. In general, very little allowance need be made for strength reduction caused by notches or abrupt changes of section in gray iron members in fatigue. The

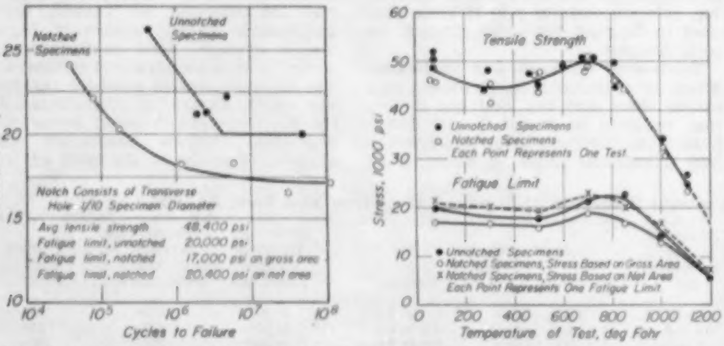

Fig. 11. S-N Curves and Effects of Temperature on Fatigue Limit of Gray Iron of the Tensile Strength Shown. Composition: 2.84% C, 1.52% Si, 1.05% Mn, 0.07% P, 0.12% S, 0.31% Cr, 0.20% Ni, 0.37% Cu (W. Leighton Collins and James O. Smith, Proc ASTM, 41, 797, 1941)

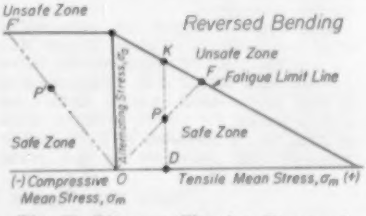
Unsafe Zone
F′
Reversed Bending
K
Unsafe Zone
F
Fatigue Limit Line
P′
Alternating Stress, σ_a
P
Safe Zone
Safe Zone
D
(-) Compressive Mean Stress, σ_m
O
Tensile Mean Stress, σ_m (+)

Fig. 12. Diagram Showing Range of Stress for Cast Iron Subjected to Ranges of Repeated Axial Stress Superimposed on a Mean Stress. Example point P illustrates conditions of tensile (positive) mean stress; P′ illustrates compressive (negative) mean stress. The safety factor is represented by the ratio of OF to OP or OF′ to OP′. For conditions of constant mean tensile stress, DK/DP is the safety factor.

lower-strength irons exhibit slight reduction in strength in the presence of fillets and holes. That is, the notch sensitivity index approaches *zero;* in other words, the *effective stress concentration factor* for these notches approaches 1. This characteristic is explained by the existence of a large number of notches associated with the graphite flakes. The strength-reducing effect of these is included in the fatigue limit values determined by conventional laboratory tests with smooth bars. Higher-strength irons, however, have greater strength reduction but probably not the full theoretical value represented by the stress concentration factor. Normal stress concentration factors (see Metals Handbook, 1954 Supplement, page 97) are probably suitable for high-strength gray irons.

Selection for Pressure Tightness

Gray iron castings are widely used in pressure applications such as cylinder blocks, manifolds, pipe and fittings, compressors and pumps. An important design factor for pressure tightness is uniformity of section. Parts of relatively uniform wall section cast in gray iron are pressure tight against gases as well as liquids. Most trouble with leaking castings is encountered when there are unavoidable abrupt changes in section. Shrinkage, internal porosity, hot tears and other defects are most likely to occur where heavy and light sections adjoin.

Watertight castings are considerably less challenging to the foundryman than gastight castings. Slight sponginess or internal porosity at heavy sections either will not leak water or, if there is a slight seepage, internal rusting will soon plug the passages permanently. For gastightness, however, the castings must be quite sound.

Lack of pressure tightness in gray iron castings can usually be traced to internal porosity, sometimes called "internal shrinkage". In gray iron this seems to be a phenomenon distinctly different from the normal solidification shrinkage that often appears on the casting surface as a sink or draw, which can be cured by risering. Internal porosity or shrinkage is very difficult to prevent by even very heavy risers and is usually associated with composition.

Visible internal porosity may appear at centers of mass when the phosphorus content exceeds 0.25%. Chromium and molybdenum accentuate this effect of phosphorus, while nickel has a slight mitigating influence. Increasing the phosphorus content to 0.70% will increase the internal shrinkage, but an increase in "carbon equivalent"— total $C + 0.3(Si + P)$ — is a much more significant factor (Fig. 13). The distinctness of the two types of shrinkage, normal and internal, is evidenced by the fact that increasing carbon equivalent decreases normal shrinkage, but greatly increases internal porosity.

The effect of phosphorus may be caused in part by the fact that lowering phosphorus content also lowers the effective carbon equivalent. Some Southern foundries have justified considerable extra expense to provide low-phosphorus (0.25% max) iron for castings that must pass an air-pressure test. Lowering the carbon equivalent by reducing carbon or silicon or both, instead of phosphorus, might similarly reduce leakage of pressure castings, but other foundry problems would be increased. ASTM A278 for pressure castings requires a maximum carbon equivalent of 3.8% for castings to be used above 450 F and 0.25% P max.

In addition to composition control, good over-all foundry practice is required for producing pressure-tight castings consistently. Sand and gating must be controlled to avoid sand inclusions. A pouring temperature adequate for good fluidity must be maintained, and heavy sections should be fed wherever possible.

Selection for Impact Applications

Where high impact resistance is needed, gray iron is not recommended. Cast iron has considerably lower impact strength than either cast carbon steel or malleable iron. However, in many gray iron castings, some impact strength is important for resistance to breakage either in shipment or in use.

There is incomplete agreement on a standard impact test method for cast iron. Three methods that have been used successfully are given in ASTM A327. Most impact testing of cast iron has been used as a research tool.

In comparing cast irons for impact strength, the best irons have been shown to be those with the highest ratio of tensile strength to Brinell hardness. Impact strength by the drop-test method correlates best, empirically, with the value $(TS)^3/(Bhn)^2$, as shown in Fig. 14.

Most producers of cast iron pressure pipe use a routine pipe impact test as a control. Impact strength in pipe is valuable principally to insure against breakage in shipping and handling.

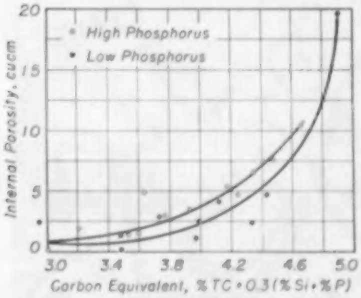

Fig. 13. Relation of Carbon Equivalent to the Internal Porosity of Gray Iron (W. C. Jeffery et al, Trans AFS, 62, 568, 1954)

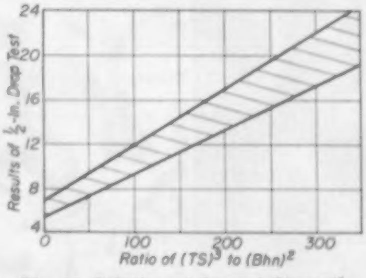

Fig. 14. Relation of Impact Strength to a Tensile-Brinell Ratio Factor in a Drop Test. Crosshatched area includes scatter of test results. (J. T. MacKenzie, Proc ASTM, 46, 1025, 1946)

Machinability

The machinability of most gray cast iron is superior to that of virtually all steel because of the graphite. Discontinuities in the matrix occupied by the graphite break up the chips, and the graphite serves as a lubricant.

In addition to the inherent machinability of cast iron, other factors are in many instances just as important for economically successful cutting. Among these factors, the following are often overlooked in tracing the origin of machining trouble:

1. The presence of chill at corners and in light sections
2. The presence of adhering sand on the surface of the casting
3. Swells, usually the result of soft molds
4. Shifted castings
5. Shrink

Chill at corners and light sections is more likely to be encountered with small castings, with higher-strength irons, and with designs that have light sections in the cope or top of the mold. Most foundries control their iron with a chill test that gives an indication of the tendency of the iron to form white or mottled iron in light sections. The foundryman may treat his iron with a small amount (1 to 5 lb per ton) of a graphitizing alloy such as ferro-silicon which effectively decreases chill. Inoculation to achieve control of the tendency to chill does not usually result in a significant change in the composition or the physical properties of the iron. Light sections, such as 3/16 in., are impracticable for an iron of higher than class 25. Class 30 iron can be cast with ¼-in. sections. These values shift with a particular design depending on how the casting is made and gated. The important thing for the engineer to understand is that the cooling in the mold at the time of freezing is the controlling variable in the formation of white or mottled iron. If the thin section is in the drag or near the gate, the flow of hot metal heats the mold and thereby decreases the rate of cooling.

If chill is encountered it is generally best to correct the trouble at its origin. It is usually uneconomical to anneal castings to remove chill. In addition to heat treating for 2 hr at 1650 F for unalloyed irons, recleaning may be required for removing scale. Distortion beyond tolerance often occurs, and there is a sacrifice in hardness and strength.

Adhering sand, mentioned above, can usually be removed by effective cleaning of the castings but sand present as the result of penetration of the iron into the mold wall is extremely difficult to blast-clean. This is a foundry defect which is best corrected at the source. Slowing speeds and increasing feeds is the best approach to salvaging castings of this type. Carbide tools are better than high speed steel for resisting the extreme abrasion of this sand.

Swells are most troublesome in operations such as broaching and in other setups tooled for high production. The additional metal often places an excessive load on the tool, which may chip or dull but not actually fail until some time after the troublesome parts have been put through the machine tool.

Shifted castings are similar to swells in their action on the cutting tools. Shifts or swells may also cause excessive tool loads if the locating points are affected. It is important to consider the positions of such locating points in design and also to avoid indiscriminate grinding of these in the foundry cleaning room.

Shrinks are not often present but can be troublesome when they are encountered in operations such as drilling. Often higher hardness is associated with an area of shrink, and this may cause the drill to break or drift from its intended path. Cast iron is the easiest metal to cast without internal shrink. The freezing of the eutectic liquid is accompanied by an expansion as the result of the precipitation of low-density graphite, which aids in obtaining internal soundness.

Because machinability is complex, it has been impossible so far to evaluate it in simple tables. Criteria such as power per unit volume in unit time are of most importance in selecting a machine tool and its motor size. Machinability ratings based on tool life under standard test conditions are helpful but are not readily interpreted into the economics of machining.

One way of indicating the effect of changing from one grade of iron to another is shown in Table XIV, from the U. S. Air Force Machinability Report, Vol. 1, 1950, page 135. Further data from this report are published in the 1954 Supplement of the Metals Handbook, page 141.

Table XIV is based on experimental data obtained by using a carbide tool and establishing a fixed amount of tool wear as the result of removing 200 cu in. of metal. The cutting speed was varied until this combination was obtained. The resulting indices of machinability serve as an approximate qualitative evaluation but not as a quantitative index. Optimum cutting feeds, speeds and finish requirements must be studied for any given machine tool setup. Tool life is an important factor since the machine must be stopped to change tools and the tools must be resharpened. Progress has been made in decreasing the machine downtime for tool changes and the resharpening cost by the use of solid carbide inserts or bits, and by other means.

Table XIV. Machinability of Gray Iron

Microstructure	ASTM Class	Tensile Strength, psi	Brinell Hardness Number	Cutting Speed,(a) fpm
Acicular iron	50	59,000	263	150
Fine pearlite, alloy	40	45,000	225	310
Ferrite (annealed)	..	15,700	100	960
Coarse pearlite, no alloy	35	35,000	195	325

(a) Cutting speed for tool life of 200 cu in. to produce 0.030-in. wear land on single-point carbide tools. Data from U. S. Air Force Machinability Report, vol. 1, 1950, p 135

Table XV. Effect of Annealing on Hardness and Strength of Class 35 Iron

Condition	Tensile Strength, psi	Brinell Hardness Number
As cast	38,900	217
Annealed	23,900	131

Composition of iron: 3.30% total C, 2.22% Si, 0.027% P, 0.18% S, 0.61% Mn, 0.03% Cr, 0.03% Ni, 0.14% Cu, Mo nil. Annealing treatment: 1 hr at 1425 F, cooled in furnace to 1000 F

The greatly improved machinability of annealed gray iron has been advantageous to automotive and other industries for many years. Annealing is usually of the subcritical type, such as 1 hr at 1350 to 1400 F. Some employ a cycle of heating to 1450 to 1500 F and cooling at 40 deg per hr to 1100 F. These treatments graphitize the carbide in the pearlite and result in a ferritic matrix. Finding it uneconomical to graphitize primary carbide, most users try to avoid obtaining it.

Annealing for improved machinability is most economical when the casting is small and the amount of machining large; a typical example is an automotive carburetor body.

The annealing treatments described result in a sacrifice of hardness and strength. A typical class 35 iron will be downgraded to about class 20 in strength by this treatment. In applications where wear resistance is important, such as cylinder blocks, gray iron is not annealed because of the unsatisfactory performance obtained with a ferritic matrix.

Table XV and Fig. 15 show the results obtained in structure and strength of a Class 35 iron.

Selection for Wear Resistance

Gray iron is widely used for machine components that must resist wear. Different types of iron, however, exhibit wide differences in wear characteristics. These differences do not correlate with the commonly measured properties of the iron.

In the discussion that follows, the general conclusions are related to metal-to-metal wear under conditions of normal lubrication. Although most of the supporting illustrations are for engine cylinders, the results have wider applicability.

Characteristics of Wear. The published data on wear of gray iron are somewhat inconsistent; accelerated wear tests often do not correlate with field service experience, nor does field experience in one application necessarily agree with that in another application. Since each of several types of wear in metal may be affected by a given property (such as graphite flake size) in a different manner, variability from application to application is not surprising.

For components in sliding contact, such as engine cylinders, valve guides and latheways, the recognized types of wear are cutting, abrasive, galling and corrosive wear.

Cutting wear is caused by mechanical removal of surface metal as a result of surface roughness, and is similar to the action of a file; it usually occurs during the breaking in of new parts. Abrasive wear is caused by the cutting action of loose abrasive parti-

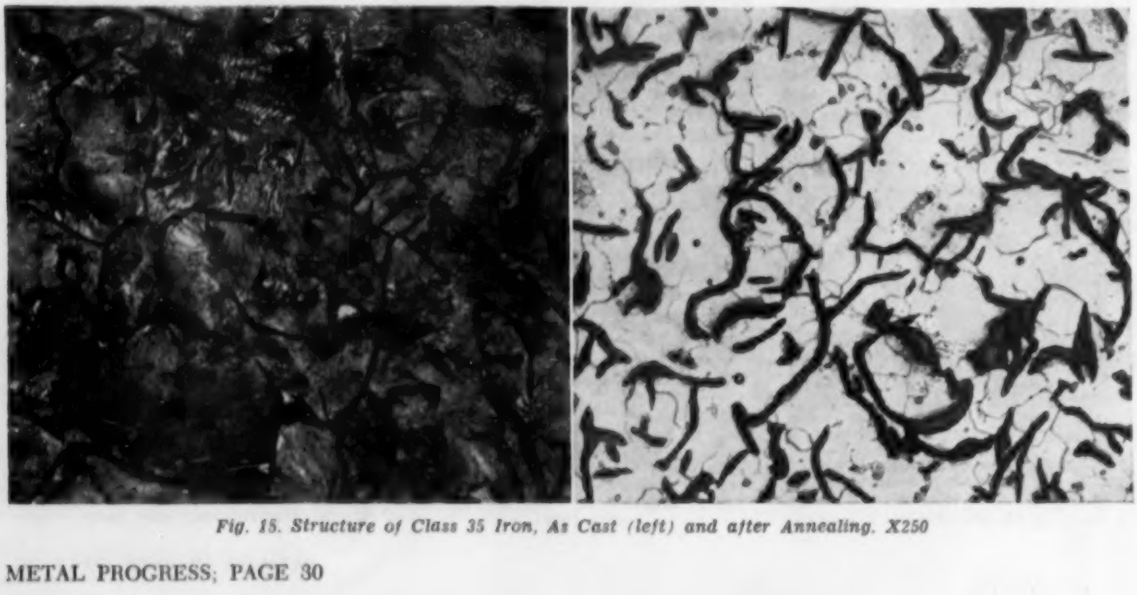

Fig. 15. Structure of Class 35 Iron, As Cast (left) and after Annealing. X250

Table XVI. Effect of Graphitic Microstructure on Resistance to Scuffing

Test No.	Type of Graphite(a)	Total Carbon, %	Resistance to Scuffing(b)
1	None	(5150 steel)	< 1(c)
2	100% Type D, centrifugally cast	3.25 (avg)	1.11
3	Type A, size 4 to 6, some Type B, centrifugally cast	3.28	1.33
4	Same as 3 except cast in sand mold	3.35 (avg)	1.30
5	Type A, size 3 to 4, some Type C, sand cast	4.00	> 1.45(d)

(a) Different chemical compositions were tested in two of the four types of iron. See Table XVIII for compositions. Matrix of all specimens was tempered martensite. (b) Expressed as the ratio of horsepower to produce scuffing divided by normal horsepower. (c) All the steel sleeves scuffed below normal horsepower. (d) Maximum available engine horsepower produced no scuffing.

Table XVII. Effect of Matrix Microstructure on Resistance to Scuffing

Test No.	Microstructure of Matrix	Hardness(a)	Resistance to Scuffing
1	Pearlite with ferrite occurring in areas of Type D graphite	196 to 227 Brinell	< 1(b)
2	Martensite tempered at 400 F	Rockwell C 53 to 56	1.06
3	Martensite tempered at 800 F	Rockwell C 44 to 47	1.22
4	Martensite tempered at 950 F	Rockwell C 39 to 41	1.39

(a) See Table XIII and Fig. 19. (b) All sleeves scuffed below normal operating range.

Table XVIII. Compositions of Irons Reported in Table XVI

No.	TC	Si	P	S	Mn	Cr	Ni	Cu	Mo
				Type D Graphite(a)					
1(c)	3.20	2.20	0.15	0.04	0.65	0.25	0.30	0.30	0.15
2	3.06	2.34	0.110	0.033	0.66	0.45	0.56	...	0.22
3	3.43	2.28	0.143	0.068	0.73	0.44	0.09	1.29	...
				Type A Fine Graphite(b)					
1	3.38	1.99	...	...	0.61	0.45	0.50	1.63	...
2	3.28	2.46	0.23	0.068	0.70	0.24	0.27	0.94	...
3(c)	3.35	2.20	0.12	0.09	0.70	0.35	0.12	1.15	...
4	3.28	2.06	0.125	0.067	0.67	...	...	0.40	...
5	3.12	2.67	0.176	0.047	0.35	0.38	0.27	1.23	0.11
				Type A Coarse Graphite					
1	4.00	1.54	0.056	0.023	0.77	...	1.39	...	0.42

(a) Corresponds to test 2 in Table XVI. (b) Corresponds to tests 3 and 4 in Table XVI. (c) Typical composition

cles that get between the contacting faces and act like a lapping compound. Galling is caused by metal-to-metal contact, resultant welding, and metal removal by breaking the welds. True galling occurs when this happens on a large scale and the metal is smeared, with resulting serious surface damage. Even in properly operating equipment some wear occurs by this process on a microscale. An intermediate form of welding wear is called scuffing—less destructive than galling but causing an abnormally high rate of metal removal. In all probability accelerated wear tests are predominantly tests of welding or scuffing wear.

Corrosive wear is a special type caused by the condensed acidic products of combustion in engine cylinders during low-temperature operation. Usually this kind of wear cannot be corrected by modifications in ordinary types of gray iron.

In well-designed machinery, wear proceeds at a slow rate and consists of combinations of mild forms of the types mentioned above. The predominant characteristic of this so-called "normal" wear is the development of a glazed surface during break-in. The primary object in any wear application is to establish conditions that produce and maintain this glaze. Beyond this is the second objective: minimizing the normal wear.

Assuming reasonable design and operating conditions for minimizing cutting and abrasive wear, the predominant abnormal wear condition that may defeat the primary objective of establishing and maintaining a glaze, is scuffing or galling caused by welding.

Resistance to Scuffing

In very extensive tests of dry wear, several alloy combinations with widely varied microstructures were tested by A. B. Shuck (Trans AFS, 56, 166, 1948). A brake-shoe type of specimen was held against a rotating gray iron drum for 1 hr after which both specimen and drum were checked for weight loss. The conditions of this test indicate that wear was caused primarily by welding, though cutting wear may have had a contributing effect. The tests covered almost all conceivable microstructures and a wide variety of compositions below 300 Bhn. The conclusions in agreement with other less comprehensive investigations were as follows:

1. Microstructure determines the wearing characteristics.
2. As graphitic microstructure becomes coarser and tends toward type A, wear is decreased.
3. Interdendritic type D graphite and its associated ferrite give very poor results.
4. Secondary ferrite associated with random type A graphite is less damaging than that associated with type D.
5. Pearlitic, acicular or tempered martensitic structures in the same hardness range are equal in wear resistance.
6. For a given type of graphite, as the matrix becomes more pearlitic and harder, wear resistance increases.

These results are substantiated in some recent scuff tests of cylinder sleeves in a diesel engine. In these tests, an engine equipped with the test sleeves was operated at constant speed, and the horsepower was increased by increments above normal until scuffing occurred. The scuffing horsepower was expressed as a ratio to normal horsepower.

Effect of Graphite Microstructure. To eliminate differences in matrix, four types of gray iron were hardened and tempered at 400 F to produce a uniform martensitic matrix. The data in Table XVI show that the greater the flake size of graphite and the more of it, the greater the resistance to scuffing. The change in casting method in tests 3 and 4 caused no significant change in scuffing. The iron of test 5 is one used in aircraft brake drums to give the maximum resistance to scoring.

Effect of Matrix Structure. Similar tests, in which the graphite was type D and the matrix was varied, gave results as shown in Table XVII. The combination of type D graphite and ferrite in test 1 is especially poor even though the rest of the structure is pearlite. Pearlitic type A iron with small amounts of free ferrite gave ratios greater than 1.33 in the same tests, showing that the results obtained with type D graphite are peculiar to the combination. Type D graphite usually occurs in combination with ferrite in as-cast irons.

The seemingly inconsistent results of this test wherein both hard and soft irons showed low resistance to scuffing, and the intermediate hardness ranges gave higher results, have been mentioned also by Paul Lane as follows: "Going from 160 to 260 Brinell in hardness results in decreasing scuffing tendencies; however, going from 260 Brinell hardness upward, including the heat treated structures, increases the tendency to scuff."

It is apparent that these tests agree with those conducted by A. B. Shuck if it is assumed that Shuck's results apply to scuffing instead of normal wear. As indicated below, Shuck's results are not in agreement with application tests on normal wear.

Other investigators have observed that a fine network of steadite (iron phosphide-iron carbide eutectic) increases scuff resistance, while massive carbide reduces it.

Effect of Chemical Composition. The diesel cylinder scuff tests for evaluating effect of graphite utilized five different compositions from five foundries for tests 3 and 4, and three compositions from two foundries for test 2. Despite the variations in composition and source, as shown in Table XVIII, all fine type A irons performed nearly alike in the scuff tests. Similarly, the three type D materials performed essentially the same. No other composition was checked with coarse type A graphite. To cover the subject of scuffing more completely, other factors were evaluated during the cylinder sleeve tests. They help to clarify some of the additional controversial aspects of wear.

Surface Finish effects were determined by running tests on honed finishes of 30 and 90 micro-in. In each, the sleeves were made from type D graphite iron, hardened, and tempered at 400 F. The results were as follows:

Micro-In.	*Scuff Resistance*
30 avg	1.11
90 avg	1.33
90 avg run under normal conditions until reduced to 20 avg, then checked	1.11

The coarser finish gives greater scuff resistance; however, this effect is lost if the finish becomes finer under normal operating conditions. The loss of scuff resistance by the smoothing effect of normal wear may account for some of the failures that occur in certain applications after break-in has apparently been successful.

This anti-scuffing effect of surface coarseness probably accounts for the special finishes on some components, such as knurling followed by grinding or honing, wherein the beneficial effect of roughness is more permanent without the detrimental effect of increased cutting wear.

Other important factors affecting scuff resistance are the material and finish of the mating part and the type of lubricant used.

Normal Wear

The scuff resistance described above should not be confused with normal wear resistance. As in scuffing, normal wear resistance is affected by both graphite and matrix microstructure, and possibly by the composition of the iron.

Some of the same sleeve materials involved in the scuff tests were operated under conditions that produced normal wear with very little evidence of scuffing. Tests were run for approximately 1000 hr, using chromium-plated compression rings on the pistons. All sleeves were hardened and tempered at 400 F. Results are given in Table XIX. Each of the three sleeve materials produced an optimum wear figure (underlined in the table). Therefore, the actual choice of sleeve material is a compromise.

Effect of Graphite Microstructure. It was concluded from the above tests that the graphite produces a surface roughening effect, which accounts for both the greater scuff resistance and the higher ring wear as the size and quantity of graphite are increased. In testing type D graphite sleeves with the rougher finish previously mentioned, improved scuff resistance was also obtained, but at the expense of greater ring wear, apparently from cutting. The larger quantity of graphite in test 3 leaves less load-carrying metal surface, and greater normal wear on the sleeve is a logical result.

The higher sleeve wear in test 1 was probably caused by slight scuffing, which gave high wear values for some sleeves tested, presumably because of the low safety margin of scuff resistance in this type of iron. Surprisingly, this mild scuffing did not seem to affect the chromium plated rings, which were apparently favored by the fine graphite. The plain gray iron oil-control rings, however, wore more in test 1 than in test 2. The principal effect of graphite on wear resistance is elimination of scuffing, and when graphite is present in greater quantity and size than required for this purpose, it will reduce normal wear resistance unnecessarily.

Effect of Matrix Microstructure. Gray iron is used for wear resistance in both the as-cast and hardened conditions. To illustrate the effect of some of the matrix variations on wear resistance, T. E. Eagan made comparable engine wear tests on seven types of gray iron cylinders, all of which apparently wore in a normal manner. A summary of his data is shown in Tables XX and XXI.

Eagan's principal conclusions are that wear is a function of microstructure and chemical composition and that, unless alloyed with chromium or molybdenum, copper is detrimental to the wear resistance of gray iron. (Some use copper to decrease chill and aid in obtaining pearlite, and in this sense copper aids wear resistance.) It also appears that best wear resistance is obtained with finer pearlite and graphite in as-cast irons.

By present standards, hardening is the most significant processing that can improve resistance to normal wear. Although iron E in Table XX showed exceptionally good wear properties, it was less resistant than the hardened iron G, and at the same time could not be cast readily into the shape required. Thus, the hardened iron was almost twice as resistant as the best practicable as-cast iron. From other extensive tests, it has been concluded that hardened iron has as much as five times greater wear resistance than pearlitic as-cast iron of the same general composition (G. P. Phillips, Foundry, Jan. 1952). Another significant advantage is that hardening automatically eliminates the variations in cast matrix microstructures, and thus provides a superior iron of more dependable performance. In most applications such as valve guides, lathe-ways, and various sliding members in machines and engines, satisfactory wear resistance is obtained with properly specified and controlled as-cast gray iron. Hardened iron is used to obtain maximum wear resistance in severe wearing applications such as high-speed diesel cylinder sleeves, camshafts, gears and similar heavily loaded wearing surfaces.

Dimensional Stability

In selecting gray iron for a part requiring dimensional stability in service, the first consideration is the operating temperature of the part in question. If this exceeds 900 F, a gray iron must be chosen that has been alloyed with a carbide-stabilizing element to prevent iron carbide breakdown and growth of the part. Gray irons with chromium content of about 1% are commonly used in the operating range from 900 to 1400 F. Table XXII indicates the effectiveness of chromium in preventing growth in cast iron.

A gray iron part that operates at an elevated temperature will deform by creep if the load is great enough. Table XXIII, giving creep characteristics of several irons at 700 F and with stresses ranging from 10,500 to 24,000 psi, clearly demonstrate the effectiveness of molybdenum additions in improving the creep properties of gray iron. Table XXIV lists typical parts that may operate above 900 F.

If the part under consideration is to

Table XIX. Effect of Type of Graphite on Wear Resistance

Test No.	Type of Graphite	Total Carbon, %	Resistance to Scuffing[a]	Sleeve Wear[b]	Ring Wear[c]
1	100% type D	3.10 to 3.40	1.11	0.003	0.002
2	Type A, size 4 to 6, some type B	3.25 to 3.50	1.30	0.020	0.027
3	Type A, size 3 to 4, some type C	4.00	1.45	0.0035	0.065

(a) See Table XVI. (b) Inches per 1000 hr. (c) Gap-increase, in. per 1000 hr

Table XX. Effect of Matrix Microstructure on Resistance to Normal Wear (T. E. Eagan)

Iron[a]	No. of Tests	Type and Size of Graphite	Matrix	Rate of Wear, in. per 1000 hr
A	28	A, size 3 to 4	Lamellar pearlite	0.0057
B	19	A, size 4	Lamellar pearlite plus phosphide	0.0012
C	4	A, size 5 to 6	Fine lamellar pearlite	0.0009
D	6	A, size 7 to 8	Very fine lamellar pearlite plus undetermined constituent	0.00097
E	30	A, size 5 to 6	Same as Iron D	0.00062
F	3	A, size 3 to 4	Lamellar pearlite plus ferrite	0.002
G	2	Not shown	Martensite	0.00048

(a) Compositions are given in Table XXI.

Table XXI. Composition of Irons Reported in Table XX (T. E. Eagan)

Iron	C	Si	P	S	Mn	Ni	Cu	Cr	Mo
A	3.00 to 3.30	1.15 to 1.35	0.20 max	0.12 max	0.90 to 1.10	.....	0.80 to 1.10	.....	.....
B	3.40 max	1.50 max	0.35 to 0.50	0.13 max	0.90 max	.....	.....	.....	.....
C	2.85 to 3.30	1.25 to 1.75	0.20 max	0.12 max	1.00 max	1.00 to 1.50	.....	0.30 to 0.40	0.25 to 0.35
D	2.80 to 3.10	4.6 to 5.0	0.20 max	0.12 max	0.80 max	.....	.....	1.90 to 2.20	.....
E	3.10 to 3.40	3.30 to 3.70	0.40 max	0.12 max	0.80 to 1.00	.....	.....	1.20 to 1.50	.....
F	3.30 to 3.40	1.75 to 2.00	0.20 max	0.12 max	0.90 to 1.10	.....	.....	.....	0.40 to 0.50
G	3.00 to 3.20	1.15 to 1.35	0.20 max	0.12 max	0.90 to 1.10	.....	.....	.....	.....

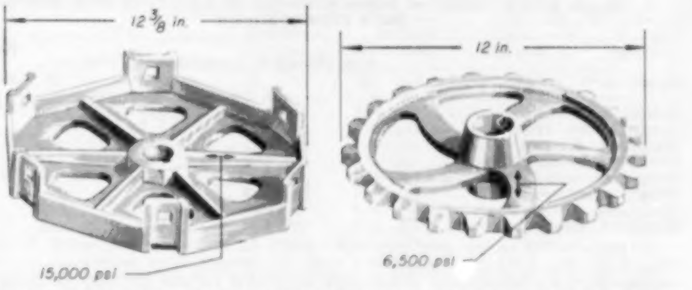

Fig. 16. Location and Magnitude of Residual Stresses in Two Gray Iron Castings

operate below 900 F, two sources of dimensional inaccuracy must be considered: residual stress and machining practice.

Residual Stresses are present in all castings in the as-cast condition and are caused by:

1. Nonuniform cooling of the surface of the casting in comparison with the center of any given cross section
2. Difference in cooling rates between sections of the same casting, because of different cross sections or locations in the mold
3. Resistance of the mold to contraction of the casting during cooling

Residual stresses in cast iron wheels have been reported as high as 32,000 psi. Magnitudes of 25,000 psi have been observed in localized areas of other gray iron castings. Residual stresses in engine cylinder blocks have been measured as high as 19,000 psi. Figure 16 shows two examples of residual stress in light castings, as determined with resistance strain gages.

If residual stresses are high enough, they may relieve themselves slightly at a very slow rate at room temperature. This is the origin of the old practice of aging castings for three months to a year before machining. However, modern methods of investigation indicate that a maximum of only 15% of the residual stress can be relieved by aging, and therefore the practice is seldom used today. Table XXV shows that aging for 84 days at room temperature had no stress relieving effect. The values of strain shown are associated with residual stresses close to the tensile strength of the class 35 iron. The reader is cautioned against using published values of the modulus of elasticity of gray iron in calculating stress from high values of strain (note Fig. 10 and also variation in Table XII).

Table XXII. Effect of Chromium in Preventing Growth of Gray Iron

Type of Iron	Growth,(a) in. per in.
Base iron(b)	0.006
Base + 0.54% Cr	0.001
Base + 1.00% Cr	0.000

(a) Growth after heating specimen to 1800 F and cooling to room temperature. (b) Composition of base iron: 3.35% total C, 2.88% graphite C, 0.47% combined C, 2.38% Si, 0.178% P, 0.106% S, 0.64% Mn, 0.17% Ni, 0.15% Cr

Only a small percentage of castings are stress relieved before machining, chiefly those requiring exceptional accuracy of dimensions or those with a combination of high or nonuniform stress associated with low section stiffness. Castings having a variety of section thicknesses or very complex designs can have especially high residual stresses. Also, castings of class 40, 50 and 60 iron are more likely to have high residual stresses.

Figure 17 shows stress relief at seven temperatures between 600 and 1100 F. The range from 900 to 1100 F is recommended.

Castings with residual stress have tension and compression balanced in the as-cast piece and are dimensionally stable at room temperature. When part of the surface is removed in machining, the balance of forces is altered. If the casting is of relatively stiff section, there may be no noticeable change in dimensions. Distortion will be most evident in castings of low stiffness from which a large volume of highly stressed metal has been removed.

Since the surface of a casting is often the principal site of residual stresses, a large proportion of the stress is relieved by rough machining, with consequent maximum distortion. If, before final machining, the casting is relocated carefully and properly supported in the machine-tool fixtures, acceptable dimensional accuracy will usually be obtained in the finished piece.

Table XXIV. Typical Gray Iron Parts That May Operate Above 900 F

Part	Approximate Operating Temperature Range, °F
Permanent molds	500 to 950
Cylinder heads	450 to 1000(a)
Exhaust manifolds	300 to 1200
Valve seat inserts	800 to 1300
Furnace castings such as grates and frames	500 to 1400

(a) Locally

Table XXV. Effect of Aging Time at Room Temperature on Residual Strain

Time, days	Residual Strain, micro-in. per in.
0	3030
21	2880
49	2860
63	3020
84	2955

Observed differences are much less than the variation expected from experimental error and from the normal differences among the five different test castings.

In designing fixtures, it must be recognized that the usual gray iron (class 30) has a modulus of elasticity of about 14 million psi, which means that the deflection under tool bit loads will be approximately twice as great in cast iron as in a steel part having the same section. The following example illustrates the importance of using proper fixtures to support gray iron castings during machining:

The part to be machined was a class 30 iron wire-drawing sheave of 31½ in. OD with a single machined groove. The thickness of the sheave rim was ⅞ in. and the rim was connected to the center hub by six spokes, ranging from ½ to ¾ in. thick. Before machining, the casting was stress relieved at 950 to 1000 F. After a group of these castings had been machined, a wavy condition appeared at the rim, ranging from 0.030 to 0.050 in., as shown by indicator readings.

Investigation of the machining practice disclosed that the fixture used to hold this sheave during the machining operation was constructed of a large steel ring 5 in. wide by 3 in. thick, which received the rim of the sheave casting on three set screws 120 deg apart. Between each pair of set screws were four spring-loaded pins to furnish further support to the sheave rim during machining.

A new fixture designed for this part eliminated point support for the casting during machining, and reduced the rim variation to a maximum of 0.006 in., which was acceptable.

It is difficult to make general state-

Table XXIII. Results of Creep Tests of Gray Iron at 700 F(a)

Total Carbon, %	Graphitic Carbon, %	Si, %	Alloying Element,(b) %	Tensile Strength, psi	Bhn	End Limit, psi	Stress, psi	Deformation, mils per in. per hr: 0 to 150 hr	150 to 450 hr	450 to 900 hr	900 to 1200 hr	1200 to 2000 hr
3.40	2.70	1.80	None	31,500	197	14,500	10,500	12.1	12.1	8.9	3.4	3.0
2.95	2.10	2.45	None	45,000	237	22,500	10,500	5.2	5.3	5.3	3.4	0.0
3.20	2.60	1.15	Ni 1.50	44,500	230	17,500	10,500	...	8.2(c)	5.2	0.0	0.0
2.75	2.27	2.10	Mo 0.83	59,500	241	...	10,500	0.8	0.8	2.2	0.0	0.0
2.72	2.06	2.50	Mo 0.83	52,500	241	...	17,300	10.0	0.0	0.0	0.0	..
2.72	2.06	2.50	Mo 0.83	52,500	241	...	19,500	16.7	3.7	0.0	0.0	..
2.72	2.06	2.50	Mo 0.83	52,500	241	...	24,000	30.0	6.7	1.6	0.0	..

(a) Symposium on Cast Iron, AFA and ASTM, 1933. (b) Also about 0.2% max P, 0.1% max S, 0.7% Mn, except the nickel iron which was 0.15%. (c) 0 to 500 hr.

ments concerning the dimensional stability that can be achieved in a gray iron casting without stress relieving. However, it is well known that automotive engine blocks are taken directly from the foundry without stress relieving and are machined to tolerances of ±0.0002 in. in such areas as crankshaft bearings, camshaft bearings and cylinder bores. Therefore, if a casting is properly designed, and cast under controlled conditions, and if proper machining practice is followed, extremely high dimensional stability can be obtained in many applications without stress relieving the castings.

Table XXVI illustrates the effect of a stress-relief heat treatment on cylinder sleeves for a tractor engine. The data show no consistent improvement of dimensional stability as a result of stress relieving. Similar results have been obtained for gray iron pistons.

Table XXVI. Effect of Stress Relieving on Alloy Gray Iron Sleeves for a Tractor Engine

Condition[a]	Avg Change in Dimensions,[b] 0.001 in. A	B	C	D	Rockwell B Hardness
Rough, as cast	− 3	− 3	− 6	− 9	96.5
Rough, stress relieved	− 4	− 5	− 3	− 7	97.5
Machined, as cast	+ 8	+11	+10	+26	95.0
Machined, stress relieved	+ 8	+ 9	+ 9	+24	97.0
Rough, as cast	− 2	− 3	− 3	− 7	95.5
Rough, stress relieved	− 1	− 2	− 2	− 4	96.0
Machined, as cast	+ 9	−10	+ 9	+30	95.0
Machined, stress relieved	+ 9	+12	+12	+33	95.0

(a) Composition of the iron was: 3.35 ± 0.15% C, 2.15 ± 0.15% Si, 0.20% P, 0.12% S, 0.65 ± 0.15% Mn, 0.60 ± 0.20% Cu, 0.20 ± 0.15% Cr. Where stress relieving was used, the castings were heated slowly to 1025 F, held 12 min and furnace cooled to 700 F. (b) Each number is the average of measurements on ten castings. A, B and C are diametral measurements; D is a change in a dimension originally 1.000 in. on the surface of the casting. The negative sign indicates a closure after a strip was cut from the casting; the positive sign indicates an opening of the sleeve.

Effect of Shakeout Practice

The shakeout practice used by the foundry may be influential in establishing the pattern of residual stresses in castings, since the basic cause of most residual stresses is the different cooling rates of light and heavy sections, which cause the casting to contract differently in these sections. This differential contraction may cause the casting to rupture in the mold ("hot crack") or, if the iron has adequate ductility at high temperature, plastic flow may occur without hot cracking. However, a casting that has undergone localized plastic flow because of the temperature variation, is likely to have some residual stress when it reaches room temperature. Areas that were hottest in the mold will generally be too short in relation to those that were colder, and the casting may be distorted or left with high residual stress.

It is not always possible to help this condition by a long delay before dumping the mold, though this is beneficial in many instances. Each casting must be analyzed to determine the influence of different practices on decreasing the temperature difference between sections. Castings with cores, such as a barrel core in a heavy-walled cylinder, may be aided by dumping while quite hot and knocking out the core, which may be a significant heat reservoir. Radiant cooling of thin outer shells must be taken into consideration, since this is generally much more rapid than cooling of metal jacketed on either side by core sand.

In addition to its effect on residual stress, shakeout practice may influence the microstructure and hardness of gray iron castings. If the iron is austenitic at the time the mold is dumped, higher hardness may result. Many types of microstructure may be obtained, since the austenite in thin sections may transform in the mold, whereas in heavier sections that cool more slowly the transformation may be delayed until the air cooling after shakeout. In general, the effect of shakeout practice on hardness is negligible in unalloyed irons. Alloy irons are the most sensitive. The martensitic irons that contain enough alloying elements to reach full hardness with slow cooling in the mold will display little, if any, difference. Table XXVII gives data for two irons.

Table XXVII. Effect of Shakeout Practice on the Hardness of Gray Iron Castings

Time,[a] min	Bhn
Class 30 Iron[b]	
5	241
6	235
8	235
20[c]	229
Class 40 Iron[d]	
3	302
6	302
10	293
12	269
20	248

(a) Time interval between pouring and shakeout. (b) Composition: 3.35% C, 2.40% Si, 0.65% Mn. Casting of 8-lb wt, avg section ⅝ in., poured at 2600 F. (c) Castings were below 1000 F 20 min after pouring. (d) Composition: 3.40% C, 2.10% Si, 0.60% Mn, 0.40% Cr, 0.93% Mo. Casting weighing 2.3 lb, with average section of 7/16 in., poured at about 2600 F

Alloying to Modify As-Cast Properties

The term "alloying" as used here does not include inoculation, since by definition the effect of inoculating on the mechanical properties of an iron is greater than can be explained by the change in chemical composition.

Strength and hardness, resistance to heat and oxidation, resistance to corrosion, electrical and magnetic characteristics, and section sensitivity can be changed by alloying, which has extended the application of gray iron into fields where costlier materials have normally been used.

There has also been considerable replacement of unalloyed gray iron by alloyed iron in applications where greater service life or greater safety factors are required and where greater service demands are put on engine castings by increasing horsepower and speeds.

The use of alloy iron often depends, in practice, on the relative production requirements in a given foundry. When the applications for alloy iron in a given plant are a small fraction of the total production, manufacturing policy may dictate the use of unalloyed iron for all castings in order to achieve maximum uniformity of production practice. Continuous production of 1000 to 3000 lb of alloy iron is usually needed for economical utilization.

The most effective single element in increasing the strength of irons is molybdenum. Chromium, nickel and copper can also be used to advantage. In many irons a combination of the elements will be most effective.

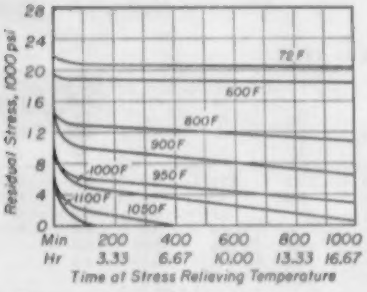

Fig. 17. Stress Relief of Gray Iron at Various Temperatures (J. H. Schaum, Trans AFS, 61, 646, 1953)

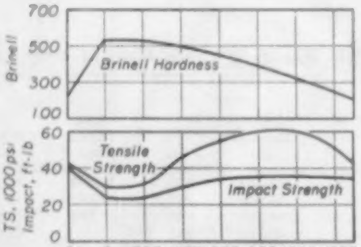

Fig. 18. Changes in Mechanical Properties of Gray Iron with Tempering Temperature

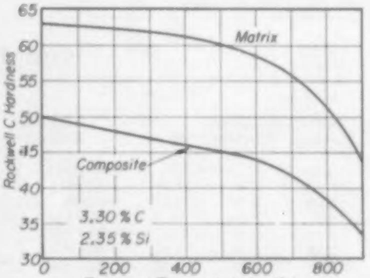

Fig. 19. Effect of Tempering Temperature on the Hardness of Quenched Gray Iron

Table XXVIII. Hardness of Quenched Samples of Gray Iron

Condition	Plain Cast Iron Combined Carbon, %	Plain Cast Iron Brinell Hardness	Cr-Ni-Mo Cast Iron Combined Carbon, %	Cr-Ni-Mo Cast Iron Brinell Hardness
As cast	0.69	217	0.70	255
After quenching from:				
1200 F	0.54	207	0.65	250
1250	0.38	187	0.63	241
1300	0.00	170	0.50	229
1350	0.00	143	0.47	217
1400	nil	137	0.45	197
1450	0.05	143	0.42	207
1500	0.47	269	0.60	444
1550	0.59	444	0.69	514
1600	0.67	477	0.76	601

Data from G. A. Timmons, V. A. Crosby and A. J. Herzig, Trans AFS, 49, 397 (1941). Specimens were 1.2-in. diam bars, 2 in. long, quenched in oil from temperatures shown.

For developing resistance to the softening effect of heat and protection against oxidation, chromium is the most effective element. It stabilizes the iron carbide and therefore prevents the breakdown of carbide at elevated temperatures; 1% Cr gives adequate protection against oxidation up to 1400 F in many applications. For temperatures above 1400 F the chromium content should be greater than 15% for protection against oxidation. This percentage of chromium changes the material to a white alloy iron.

For corrosion resistance, chromium, copper and silicon are effective. Amounts from 0.2 to 1.0% Cr decrease the corrosion rate in sea water and weak acids. The corrosion resistance of iron to dilute acetic, sulfuric and hydrochloric acids and acid mine water can be increased by addition of 0.25 to 1.0% Cu. For sulfur and acid corrosion, 15 to 30% Cr is effective. Silicon additions in the range of 14 to 15% give excellent corrosion resistance to sulfuric, nitric and formic acids; however, both high-chromium and high-silicon irons are white; the high-silicon irons are extremely brittle.

The electrical and magnetic properties of cast iron can be modified slightly by minor additions of alloying elements, but a major change in characteristics can be accomplished by use of approximately 15% Ni, or nickel plus copper, which results in an austenitic iron that is virtually nonmagnetic. The austenitic gray irons also have good resistance to oxidation and growth up to 1500 F.

Molybdenum is the most effective element in modifying section sensitivity and is normally added in amounts of 0.5 to 1.0%.

Base Irons. The selection of alloying elements to bring about modification of as-cast properties in gray iron depends to a large extent on the composition and method of manufacture of the base iron. For example, a foundry producing a base iron of 2.3% Si and 3.4% total C for automotive castings might add 0.5 to 1.0% Cr if required to make heavier castings with the same hardness and strength as the normal castings. However, a foundry producing a base iron of 1.7% Si and 3.1% C for a heavy casting would add 0.5 to 0.8% Si to decrease hardness and chill when pouring their iron in light castings.

Depending on the strength desired in the final iron, the carbon equivalent of the base iron may vary from approximately 4.4% for weak irons to 3.0% for high-strength irons. The method of producing the base iron will affect mechanical properties and the alloy additions to be made, since factors such as type and percentage of raw materials in the metal charge, amount of superheat, and cooling rate of the iron after pouring, all affect the properties. The base iron used for alloying will vary considerably from foundry to foundry as will the alloying elements selected to give the desired mechanical properties. However, parts produced from different base irons and alloy additions can have the same properties and perform the same in service.

A typical base iron in a foundry producing automotive castings contains 3.35 ± 0.15% total C, 2.15 ± 0.15% Si, 0.14% S, 0.15% P and 0.65 ± 0.15% Mn. Typical transverse strength of such an iron as cast, would be 2200 lb (1.2-in. diam bar, 18-in. centers); tensile strength, 30,000 psi (1.2-in. diam bar); and Brinell hardness, 179 to 241.

Examples of how the above base iron can be modified for various applications in automotive parts are as follows:

1. For resistance to growth, oxidation and heat checking, and for application as heavy-duty diesel and gas engine cylinder heads, brake drums and exhaust manifolds, a typical composition, after alloy addition to the base iron, would be: 3.35% total C, 2.15% Si, 1.25% Ni and 0.65% Cr (with other elements unchanged). This will result in average transverse strength, as cast, of 2400 lb; transverse deflection, 0.26 in.; tensile strength, 35,000 psi; and Brinell hardness, 179 to 277. This alloy addition would increase the cost of the metal in a typical casting by 1.6¢ per lb of iron.
2. Castings requiring strength, such as a differential case, could have the base iron modified to the following typical composition: 3.25% total C, 2.15% Si, 0.30% Ni, 0.25% Cr and 0.60% Mo. This iron would have average transverse strength, as cast, of 2700 lb; transverse deflection, 0.30 in.; tensile strength, 45,000 psi; and Brinell hardness, 196 to 277. This alloy addition would cost about 1.8¢ per lb of iron.
3. Castings requiring resistance to heat and to corrosion by fuel, as in a diesel engine precombustion chamber, can be modified to the following typical composition: 3.35% total C, 2.40% Si and 1.05% Cr. This would result in test bars having average transverse strength, as cast, of 2600 lb; transverse deflection, 0.28 in.; tensile strength, 40,000 psi; and Brinell hardness, 187 to 269. The cost of the alloy addition to make this modification to the base iron would be about ½¢ per lb of iron.

Heat Treatment

Gray iron, like steel, can be hardened when cooled rapidly or quenched from a suitable elevated temperature. The quenched iron may be tempered by reheating in the range from 300 to 1200 F to increase toughness and relieve stresses. The quenching medium may be water, oil, hot salt or air, depending on the composition and section size. Heating may be done in a furnace for hardening throughout the cross section, or it may be localized as by induction or flame so that only the volume heated above the transformation temperature is hardened. In the range of composition of the most commonly used unalloyed gray iron castings—that is, about 1.8 to 2.5% Si and 3.0 to 3.5% total C — the transformation range is from about 1400 to 1550 F. The higher temperature must be exceeded in order to harden the iron during quenching.

During the heating of unalloyed gray iron for hardening, graphitization of the matrix frequently begins as the temperature approaches 1100 to 1200 F and may be entirely completed at a temperature of 1350 to 1400 F. This temperature range is used for maximum softening.

The changes in combined carbon content and hardness that occur on heating and quenching both alloyed and unalloyed gray iron are shown in Table XXVIII.

Ordinarily gray iron is furnace hardened from a temperature of 1575 to 1600 F. This results in a combined carbon content of about 0.7% and a hardness of about Rockwell C 45 to 52 (415 to 514 Brinell) in the as-quenched condition. Temperatures much above this are not advisable because the as-quenched hardness will be reduced by retained austenite.

Oil is the usual quenching medium for through hardening. Quenching in water may be too drastic and cause cracking and distortion unless the castings are massive and uniform in cross section. Hot oil and hot salt are sometimes used as quenching mediums to minimize distortion and quench cracking. Water is often used for quenching with flame or induction hardening where only the outer surface is hardened.

Hardenability. The hardenability of unalloyed gray iron is about equal to that of low-alloy steel of similar matrix carbon content. The hardenability can be measured with the standard end-quench hardenability test employed for steels. The hardenability of cast iron is increased by the addition of chromium, molybdenum or nickel. Gray iron can be made air-hardenable by addition of the proper amounts of these elements. Some typical data on hardenability of plain and alloyed irons are shown in Table XXIX. Compositions of the irons are listed in Table XXX.

Mechanical Properties. As-quenched gray iron is brittle. Tempering after quenching improves strength and toughness but decreases hardness. A temperature of about 700 F is required before the impact strength is restored to the as-cast level. The tensile strength after tempering may be from 35 to 45% greater than the strength of the as-cast iron. Changes in properties brought about by quenching and tempering are shown in Fig. 18.

Heat treatment is not ordinarily used commercially to increase the strength of gray iron castings, because the strength of the as-cast metal can be increased at less cost by reducing the

Table XXIX. Hardenability Data for Gray Irons Quenched from 1575 F
(See Table XXX for compositions)

Distance from Quenched End, 1/16'ths	in.	Rockwell C Hardness Plain Iron	Mo(A)	Mo(B)	Ni-Mo	Cr-Mo	Cr-Ni-Mo
2	⅛	54	56	53	54	56	55
4	¼	53	56	52	54	55	55
6	⅜	50	56	52	53	56	54
8	½	43	54	51	53	55	54
10	⅝	37	52	50	52	56	53
12	¾	31	51	49	52	54	53
14	⅞	26	51	46	52	54	52
16	1	26	49	45	52	54	53
18	1⅛	25	46	45	52	53	52
20	1¼	23	46	44	51	50	51
22	1⅜	22	45	43	47	50	50
24	1½	22	43	44	47	49	50
26	1⅝	21	43	44	47	47	49
28	1¾	20	40	41	45	47	48
30	1⅞	19	39	40	45	44	50
32	2	17	39	40	45	41	47
34	2⅛	18	36	41	44	38	46
36	2¼	18	40	40	45	36	45
38	2⅜	19	38	37	45	34	46
40	2½	22	38	36	42	35	46
42	2⅝	20	35	35	42	32	45

G. A. Timmons, V. A. Crosby and A. J. Herzig, Trans AFS, 49, 397 (1941)

Table XXX. Compositions of Irons for Which Hardenability Data Are Given in Table XXIX

Iron	TC	CC	GC	Si	P	S	Mn	Mo	Ni	Cr
Plain	3.19	0.69	2.50	1.70	0.216	0.097	0.76	0.013	...	0.03
Mo(A)	3.22	0.65	2.57	1.73	0.212	0.089	0.75	0.47	...	0.03
Mo(B)	3.20	0.58	2.62	1.76	0.187	0.054	0.64	0.48	trace	0.005
Ni-Mo	3.22	0.53	2.69	2.02	0.114	0.067	0.66	0.52	1.21	0.02
Cr-Mo	3.21	0.60	2.61	2.24	0.114	0.071	0.67	0.52	0.06	0.50
Cr-Ni-Mo	3.36	0.61	2.75	1.96	0.156	0.070	0.74	0.47	0.52	0.35

silicon and total carbon contents or by adding alloying elements. Gray iron is usually quenched and tempered to increase the resistance to wear and abrasion by increasing the hardness. A structure consisting of graphite embedded in a hard martensitic matrix is produced by heat treatment. This process can replace the white iron surface usually produced by chilling, and can replace alloy irons in many applications with possible saving in cost. It can be applied where chilling is not feasible, as with complicated shapes or large castings, or where close tolerances are required that can be attained only by machining. Heat treatment extends the field of application of gray iron as an engineering material.

The hardness of quenched and tempered gray iron measured with either a Brinell or Rockwell C test is an integration or the resultant of the hardness of the metal matrix and the graphite. The hardness of the matrix itself, measured with a microhardness test, is generally from 8 to 10 points harder on the Rockwell C scale than the hardness indicated by the conventional Rockwell C test. This is shown in Fig. 19, which compares Rockwell C hardness with the hardness of the matrix itself measured with a Vickers indenter and 200-g load and the values converted to equivalent Rockwell C. The hardness of the matrix and the change in matrix hardness with tempering temperature are about the same as in an alloy steel of approximately 0.7% C.

After tempering at 700 F for maximum toughness, the hardness of the metal matrix is still about Rockwell C 50. Where toughness is not required and a tempering temperature of 300 to 500 F is acceptable, the matrix hardness is equivalent to Rockwell C 55 to 60. The combination of high matrix hardness and graphite as a lubricant results in a surface with good wear resistance for some applications—for instance, farm implement gears, sprockets, diesel cylinder liners and automotive camshafts.

Dimensional change resulting from hardening gray iron is quite uniform and predictable if the prior structure and composition are uniform. Such dimensional changes can be allowed for in machining before heat treatment.

Complex shapes or nonuniform sections may distort as a result of relief of residual casting stresses or differential rates of cooling and hardening during quenching, or both. The former condition can be minimized by stress relieving at 1050 to 1100 F before machining. The latter can be minimized by either marquenching or austempering; both of these processes are being used for cylinder liners where out-of-roundness must be held to a minimum. Through hardening is employed on gears, sprockets, hub bearings and clutches.

Localized Hardening. In parts where only local areas need to be hard, conventional induction hardening or flame hardening may be used. The details of these processes are discussed on pages 107 to 131 of this Supplement.

For flame hardening, it is generally desirable to alloy the iron with small amounts of either chromium or molybdenum to stabilize the iron carbide and thus prevent graphitization.

Water may be used as the quenching medium where the depth of hardening is shallow and where the part is being progressively heated and quenched. When only small areas are being hardened, the parts may be dropped into an oil quench.

Localized hardening is currently being employed for camshafts, gears, sprockets and cylinder liners.

Physical Properties

Patternmakers' rules allow ⅛ in. per ft for linear contraction of gray iron, and 3/16 to ¼ in. per ft for white iron (⅛ in. per ft is about 1%). Often this allowance is inaccurate in practice, and more exact evaluation must be made of the effects of mass, composition, shape, mold and core. Generally contraction is less with increase in mass and, in gray irons, increases with increase in tensile strength.

Three contraction phenomena are exhibited during the cooling of a cast iron from the molten state to room temperature: (1) in the liquid, about 2.8% from 2600 to the liquidus at about 2200 F; (2) during solidification, and (3) subsequent to solidification, about 3.0% from 2100 F to room temperature.

Shrinkage in volume during solidification ranges from negative shrinkage in "soft" irons to +1.94% in an iron containing about 0.90% combined C. The white irons have 4.0 to 5.5% contraction in volume within the same range of temperature.

Coefficient of Expansion. The coefficient of expansion of gray irons in the range from 0 to 500 C (32 to 932 F) is about 13×10^{-6} per °C. The expansion is about 10.5×10^{-6} per °C in the range from 0 to 100 C (32 to 212 F). The expansion varies somewhat with the type of iron and is greater in the softer and higher-carbon irons.

For the temperature range from 1070 C (1958 F) to room temperature, the coefficient of expansion varies from 9.2 to 16.9×10^{-6} per °C. At room temperature the commonly used figure of 10×10^{-6} per °C is accurate enough for ordinary changes in temperature.

Density. The density (grams per cubic centimeter) of gray irons at room temperature, varies from about 6.95 for open-grained high-carbon irons to 7.35 for close-grained, low-carbon irons. The density of white iron is about 7.70. The density of liquid cast irons just above the final solidification temperature is about 6.23. For conversion to weight in pounds per cubic foot, the values for density should be multiplied by the factor 62.428. A gray iron with density of 7.20 weighs about 450 lb per cu ft.

Thermal Conductivity. The thermal conductivity is approximately 0.11 cal per cm per °C per sec.

Electrical and Magnetic Properties. As compared with that of other ferrous metals, the resistivity of gray iron is relatively high, apparently because of the amount and distribution of the graphite content. Increases in total carbon content and in silicon content increase resistivity.

Hatfield states as follows: "....the magnetic properties of cast iron may vary within very wide limits, ranging from those of materials having low permeability and high coercive force suitable for permanent magnets, and those having high permeability, low coercive force, and low hysteresis loss suitable for electrical machinery".

Highest magnetic induction and permeability are found in annealed white irons, such as malleable cast iron. Flake graphite, as in gray iron, does not affect the hysteresis loss but prevents the attainment of high magnetic induction. The flakes and attendant discontinuities cause small demagnetizing forces.

The Selection and Application of Stainless Steel in the Chemical Process Industries

By the ASM Committee on Stainless Steel in Chemical Uses

THE PERFORMANCE of stainless steels in the chemical process industries can be affected adversely by (1) general corrosion, (2) intergranular corrosion, (3) stress-corrosion cracking, and (4) pitting. Frequently, minor variations in environment will have a marked effect on the service life of stainless steel. Design and fabrication practices may also greatly influence performance.

The applications discussed in this article and the data included on page 41 are limited to chemical solutions that carbon steel and other metals cheaper than stainless steel do not resist satisfactorily.

General Corrosion

The stainless steels owe their unusual corrosion resistance to a condition known as "passivity", believed by most investigators to result from the presence of thin films of oxide called "passive films". It is generally agreed that under favorable conditions (usually oxidizing) such films are protective; unfavorable conditions destroy the films and leave the surface in the "active" state, with corrosion resistance only slightly superior to that of ordinary iron or steel. Passivity exerts a greater influence on the resistance of stainless steels to corrosion than on resistance of most other commonly used metals and alloys. Passivity is readily developed by treatment with any of a number of oxidizing solutions or merely by exposing a chemically cleaned surface to air.

Sometimes only slight changes in environment will change the passive to the active state or vice versa; consequently, conditions of so-called "borderline passivity" can cause unpredictable variations in resistance to general corrosion. Dilute sulfuric acid solutions, especially when hot, are notorious in this respect. The presence of air or small amounts of an oxidizing agent, such as nitric acid, can maintain passivity under otherwise corrosive conditions. The hydrogen released from the corrosion of another material in the system may be sufficient to destroy passivity under conditions that would be satisfactory otherwise. Many other reducing agents have the same effect.

That oxidizing conditions favor passivity is proved by the outstanding performance of types 304, 347 and 430 in services involving nitric acid. (Table I identifies the stainless steels mentioned in this article.) However, conditions may be too strongly oxidizing. With concentrations greater than about 95% at atmospheric temperature, or even with relatively low concentrations at temperatures above the atmospheric boiling point, nitric acid solutions become corrosive to stainless steels.

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Halide acids and acid halide salts may destroy passivity. Resistance to such compounds should be questioned unless reports of previous experience or dependable test results on stainless steels are available. As a class, the stainless steels are only moderately resistant to sulfuric acid solutions unless oxidizing conditions exist. Types 316 and 317, which contain molybdenum, are more resistant; so are more highly alloyed steels containing both molybdenum and copper. The resistance to corrosion by phosphoric acid solutions is similar to resistance to sulfuric acid solutions, but the allowable ranges of concentration and temperature for acceptable performance are somewhat greater for phosphoric than for sulfuric acid.

Supplements the section on Stainless Steels, pages 549 to 562 of the 1948 ASM Metals Handbook

Organic acids can generally be handled safely with the austenitic types 304, 316, 317 and 347. Under the most severe conditions, especially with hot concentrated vapors or condensates, the molybdenum-bearing grades show definite superiority. Resistance to alkaline conditions is also good, but satisfactory materials are usually available at a lower cost. The stainless steels, especially the 300 series, are generally resistant to solutions of inorganic or organic salts, with the exception of halide salts, as mentioned previously.

In applications involving borderline passivity, types 316 and 317 extend the range of permissible operation. Sometimes processing conditions may be altered to restore or preserve passivity by aeration or the addition of an oxidizing agent or, in service with sulfuric acid solutions, by adding small amounts of copper sulfate continually. If corrosion develops where performance has been satisfactory, it is almost certain that some slight and correctable change in operating conditions has been responsible for the destruction of passivity.

In general, the ferritic grades of stainless steel show a narrower range of acceptability than the austenitic grades.

Intergranular Corrosion

Improper heat treatment of stainless steels can cause early failure under severely corrosive conditions and a greatly reduced life in many relatively mild services. The unstabilized austenitic steels that contain more than 0.03% C and no columbium or titanium, become susceptible to intergranular corrosion because complex chromium carbides precipitate in grain boundaries when the steel is exposed to temperatures from about 800 to 1500 F. Normal welding procedures induce susceptibility to this condition. The fact that a stainless steel is susceptible to intergranular corrosion does not necessarily mean that it will be so attacked; service may be satisfactory. However, many corrosive mediums, including some considered only mildly corrosive, will corrode susceptible steels intergranularly. The possibility of intergranular attack must be recognized unless ruled out by previous experience.

Chromium carbide precipitation and its effects can be eliminated by:

1 Heating the steel, after final fabrication or processing, to a temperature high enough to dissolve the carbides

Table I. Composition Limits of Stainless Steels Mentioned in This Article

Type	C (max)	Cr	Ni	Mo	Other
			Wrought Alloys		
Austentic Steels					
304	0.08	18.00 to 20.00	8.00 to 12.00	....	....
304L	0.03	18.00 to 20.00	8.00 to 12.00	....	....
309	0.20	22.00 to 24.00	12.00 to 15.00	....	....
309S	0.08	22.00 to 24.00	12.00 to 15.00	....	....
310	0.25	24.00 to 26.00	19.00 to 22.00	....	....
316	0.08	16.00 to 18.00	10.00 to 14.00	2.00 to 3.00	....
316L	0.03	16.00 to 18.00	10.00 to 14.00	2.00 to 3.00	....
317	0.08	18.00 to 20.00	11.00 to 15.00	3.00 to 4.00	....
321	0.08	17.00 to 19.00	9.00 to 12.00	....	Ti 5 × C min
347	0.08	17.00 to 19.00	9.00 to 13.00	....	Cb-Ta 10 × C min
20 (not std)	0.07	20.00	29.00	2.00	3 Cu
329 (not std)	0.10	23.00 to 28.00	3.00 to 5.00	1.00 to 2.00	....
Ferritic Steels					
430	0.12	14.00 to 18.00	....	....	....
446	0.20	23.00 to 27.00	....	....	N 0.25 max
443 (not std)	...	20.00	....	....	1 Cu
			Cast Alloys[a]		
CB-30	0.30	18.00 to 22.00	2.00 max	....	....
CC-50	0.50	26.00 to 30.00	4.00 max	....	....
CF-8	0.08	18.00 to 21.00	8.00 to 11.00	....	....
CF-8M	0.08	18.00 to 21.00	9.00 to 12.00	2.00 to 3.00	....
CF-8C	0.08	18.00 to 21.00	9.00 to 12.00	....	Cb 8 × C min, or Cb-Ta 10 × C min
CK-20	0.20	23.00 to 27.00	19.00 to 22.00	....	....
CN-7M	0.07	18.00 to 22.00	21.00 to 31.00	....	Mo-Cu
CH-20	0.20	22.00 to 26.00	12.00 to 15.00	....	....
CH-10	0.10	22.00 to 26.00	12.00 to 15.00	....	....

(a) Cast alloys are normally characterized by higher silicon and chromium contents than the corresponding wrought grades. For similar grades, see box below.

(usually 1900 to 2100 F) and cooling rapidly enough to avoid reprecipitation. Localized heat treatment of the area immediately adjacent to a weld is not satisfactory for the prevention of chromium carbide precipitation. For effective heat treatment, the entire unit must be heated and quenched.

2 Using a stainless steel that has been stabilized with columbium or titanium, which combines with the carbon and thereby prevents harmful precipitation of chromium carbides. The stabilized steels are required for service that involves long exposure within the temperature-sensitive range (800 to 1500 F) or a corrosive condition severe enough to attack susceptible steel intergranularly.

3 Reducing the carbon content to such a low level that difficulty is avoided. The availability of extra-low-carbon steels (types 304L and 316L) during the past few years has made this third method of great practical importance.

Among the methods available for the detection of susceptibility to intergranular corrosion are the boiling 65% nitric acid (Huey) test, the acidified copper sulfate (Strauss) test, the nitric-hydrofluoric acid test and, quite recently, the oxalic acid etch test. For the unstabilized grades, the test is made on specimens representing the condition in which the steel would be used. In tests performed on stabilized or extra-low-carbon grades to determine whether the steel as supplied is resistant to sensitization, the specimen is sensitized by heat treatment in the temperature-sensitive range (for example, 1 hr at 1250 F) to reveal its susceptibility.

The nitric acid test is not ordinarily used for routine evaluation of types 316L and 321 because phenomena other than chromium carbide precipitation can cause these steels to corrode intergranularly in nitric acid. Intermetallic compounds of iron and chromium, known as sigma and chi phases, or perhaps transition phases intermediate in the formation of sigma and chi may be responsible for this effect.

The danger of chromium carbide precipitation is now so widely recognized and guarded against that few failures occur from this cause.

In atmospheric exposure or mildly corrosive conditions where freedom from contamination is the primary objective, precautions against intergranular corrosion are not usually required. However, for applications where this trouble might occur, it can be prevented by using either stabilized or extra-low-carbon grades, or by heat treatment after fabrication.

"Knife-Line Attack" is a special form of intergranular corrosion sometimes encountered on type 321 and to a lesser degree on type 347. It usually occurs when welded equipment is subjected for a considerable period of time to temperatures within the sensitizing range after fabrication as, for instance, in a stress relieving treatment. After such a treatment, the metal immediately adjacent to the welds may be attacked by corrosive mediums. The explanation is that the affected area has been heated to a temperature high enough to decompose the titanium or columbium carbides. Consequently, a part of the carbon combines with chromium during subsequent exposure within the most favorable temperature range for chromium carbide precipitation. The metal is therefore made susceptible to intergranular corrosion.

Corresponding Grades of Stainless Steel

Wrought	*Cast*
304	CF-8
309	CH-20
309S	CH-10
310	CK-20
316	CF-8M
347	CF-8C
20	CN-7M
430	CB-30
446	CC-50

Stress-Corrosion Cracking

Almost any metal or alloy, including austenitic stainless steels, can be made to fail by stress-corrosion cracking under conditions involving applied or residual stresses and specific mild corrosives. Chloride solutions are the worst offenders in promoting cracking of austenitic stainless steels, and a number of failures involving chloride compounds have occurred in industry.

A 10-in. overflow float of 304 steel cracked badly after 6 months of exposure to vapor in a deaerating water heater (Fig. 1). The water was treated city water and no evidence of chemical attack was present. It was presumed that cracking had resulted from extreme cold work in manufacture and from the changing temperature within the water heater.

Figure 2 shows a perforated backing plate of a salt (NaCl) drum filter that failed from stress corrosion. The majority of the cracks radiate from the cold perforated holes. Many slip lines were present in the vicinity of the holes, indicating extreme cold work without heat treatment. Cracking was chiefly transgranular.

Cracking has been observed in some instances even in hot water of relatively low chloride content, especially where cold worked parts were involved or where chloride was concentrated in crevices or pockets. A boiling 42% magnesium chloride solution is especially severe in this respect (Fig. 3) and has been used as a basis of comparison in laboratory work.

As-drawn or severely cold worked stainless steels crack readily in systems containing aqueous hydrogen sulfide, but annealed steels are not susceptible unless they are stressed well above the yield strength. Several mediums, including strong hot caustic solutions under pressure, have been reported to cause cracking, although in most of these failures unreported chloride impurities may have been responsible. It is certain that chloride compounds have caused most of the stress-corrosion cracking in stainless steel.

The mechanism of stress-corrosion cracking has not yet been established.

Table II. Stresses in Austenitic Stainless Steel after Various Treatments

Stress Relieving Temperature, deg Fahr	Time, hr	Residual Stress, 1000 psi
After Welding 9¼-In. OD, 6½-In. ID Pipe		
As Welded	..	30.0 to 25.7
1100	16	20.0
1100	48	22.0
1100	72	23.0
1200	4	21.5 to 24.0
After Welding 5-In. OD, 4-In. ID Pipe		
As Welded	..	18.5 to 14.7
1200	4	13.7 to 15.3
1200	12	16.0
1200	36	15.6
1650	2	nil
1850	1	nil

W. L. Fleischmann, report entitled "Heat Treatments of Welded Structures for the Relief of Residual Stresses with Particular Reference to Type 347 Stainless Steel Weldments", Knolls Atomic Power Laboratory, Aug. 17, 1953.

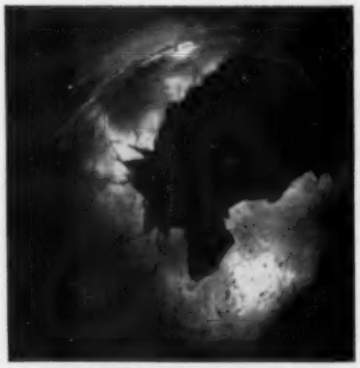

Fig. 1. Cracking and Breakage in Overflow Float of Type 304 Exposed in Vapor Space above Water Level of Deaerating Water Heater

This kind of cracking in the austenitic stainless steels is chiefly transgranular and sometimes may be accompanied by pitting attack. Heavily cold worked and as-drawn parts are most susceptible, but annealed steel can also crack under severe conditions. Cracking is much more likely to occur in hot than in cold solutions.

Stress Relieving of 304L and 316L

To avoid stress-corrosion cracking, some equipment fabricated from 304L and 316L has been stress relieved at temperatures ordinarily used for carbon steel (1000 to 1200 F). While this temperature range would be harmful to ordinary 18-8 because of carbide precipitation, it has no harmful effect on the extra-low-carbon grades.

Samples of 304L and 316L heated to 1200 F for 1 to 3 days and then tested in a modified Strauss test as prescribed by ASTM have shown no intergranular effects after three 72-hr immersions. Exposure of the low-carbon grades to temperatures in the carbide precipitation range may create harmful effects in certain corrosive media. For example, 316L may fail in the Huey test (boiling 65% nitric acid) after heating for only 1 hr at 1200 F. This may be caused by the formation of sigma at grain boundaries. The mechanism of sigma formation is similar to carbide precipitation in that there is a depletion of chromium in the adjacent areas. Depletion by sigma formation may be less severe than in carbide precipitation; this may account for the attack in boiling nitric acid but not in acidified copper sulfate.

While low-temperature stress relief may be adequate for certain corrosives, which should be evaluated, stresses are not completely removed. For complete relief of residual stress, a temperature of 1650 F is required. Table II shows the residual stresses after various stress relieving treatments of solid austenitic stainless steels. Integrally bonded or attached stainless linings on carbon steel cannot be stress relieved effectively by heating because of the large difference in the coefficients of expansion.

If the stress level at which stress corrosion may occur is known to be below that expected after stress relieving at a low-temperature, such a stress relief should be practical. If the stress levels are not known, the high-temperature stress relief should be considered.

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Weld deposits exposed to this temperature range sometimes are affected adversely by corrosion, and the use of columbium-stabilized electrodes may be advantageous. Extra-low-carbon weld metal is not guaranteed below 0.04% C.

Pitting or Localized Corrosion

Since the stainless steels are passive under almost all conditions in which they are normally used, any localized corrosion, under circumstances that prevent restoration of passivity, may cause rapid penetration at the point of initiation. This is because an active-passive electrolytic cell is formed between the large cathodic (passive) area and the small anodic area under attack; the surrounding oxygen serves as a depolarizer, and pitting proceeds.

Solutions containing chlorides are especially detrimental because they promote the formation of such cells, and severe pitting may result. Acid chlorides in their higher valence state, such as cupric chloride ($CuCl_2$) and ferric chloride ($FeCl_3$), are particularly severe in this respect, but any chloride in appreciable concentration is a source of possible trouble. Solutions of other halide salts and of some sulfates may cause pitting. Localized attack is also induced by stagnant conditions that occur in cracks or crevices or at joints made with gaskets. Depending on the type of gasket, galvanic couples may be formed at such joints.

The molybdenum in types 316 and 317 increases resistance to pitting, although this is a matter of degree, and localized attack will still occur under severe conditions. Elimination of cracks, crevices and stagnant pockets, as far as possible, and the use of clean surfaces will minimize possibilities for trouble.

Design and Fabrication

Failures can often be eliminated by suitable changes in design without changing the type of steel. Factors to be considered include joint design, surface continuity, and concentration of stress. Welds should be well spaced, and the ASME code should be followed for location and manner of making the attachments. Welds should also be located to permit economical cutting of plates and good fit-up at joints. Butt welds are preferable to lap welds. If lap welds are necessary, they should be completely sealed against penetration by corrosive solutions; otherwise crevices or cell-corrosion failures may result. The use of attachments, such as doubling or reinforcing plates encircled by fillet welds, should be minimized because these produce residual bi-axial stresses that are generally more difficult to relieve by heat treatment. In order to avoid the diffusion of carbon into stainless steel tanks from the mild steel supporting legs, the legs should be welded to a stainless steel saddle that is welded to the bottom of the tank.

Wherever possible, welding should be done in the downhand position to produce sound welds. With manual welding methods, stringer beads are preferable because heat effect is decreased

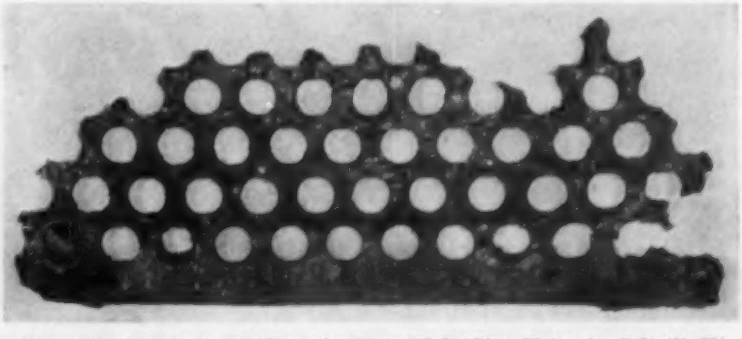


Fig. 2. Stress-Corrosion Failure of a Type 347 Backing Plate of a Salt (NaCl) Drum Filter

and residual stress is minimized. Water cooling of welds less than 3/16 in. thick may lessen heat effect and distortion. Although such control of heat-affected zones is unnecessary with the stabilized (321, 347) or extra-low-carbon steels (304L, 316L), freedom from residual fabricating stresses is important, particularly where susceptibility to stress-corrosion cracking exists. Poor fit-up causes stresses from the forcing of parts into position or from poor welds at gaps and unevenness in the joints. Weld deposition sequences should be used that will minimize residual stresses.

Equipment should be thoroughly cleaned to remove all contamination such as oxides and iron dust, weld spatter, welding flux, dirt and organic matter. These may be removed by blast cleaning or pickling. There should be a final cleaning with a solution of 10% nitric - 1% hydrofluoric acid.

The elimination of notches, threads, grinding or abrasive scratches, corners, grooves or similar stress raisers is essential. Generous fillets at corners, smooth contour welds without undercutting, ground and polished welds, rounded corners, ground and polished edges and flat surfaces will eliminate causes of stress concentration.

Cold forming operations, such as rolling tubes into tube sheets, should be held to a minimum. Severe forming operations, such as rolling dished heads for tanks, should be done by hot working above 1600 F. Castings, bolts, tank ends and other hot formed components should be annealed at 2000 F and quenched in water or air blast.

If heat treatment is required, consideration should be given to the structural stability of the equipment at the high temperature that will be encountered. Surfaces must be clean and free from carbonaceous materials such as oil, grease and paint, which may increase the carbon content of the steel by absorption at the temperatures of heat treating. Availability of heat treating facilities in the locality where the equipment is to be fabricated will influence cost. Sometimes the higher-priced stabilized or extra-low-carbon grades may reduce the cost of equipment by eliminating heat treatment.

Corrosion Testing

Since reproduction of actual service conditions is difficult in laboratory tests, results of such tests often can serve only as a guide. Chemical conditions, temperature, velocity and aeration should parallel those in the proposed process; therefore field tests in existing equipment in a comparable process should be used wherever possible in order to duplicate the conditions. If the installation will be expensive to fabricate and install, the tests should be made in a pilot plant to provide more realistic results.

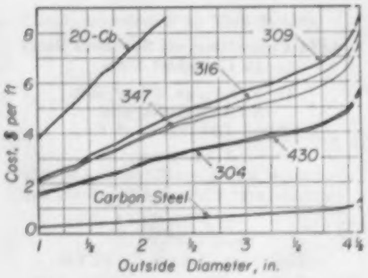


Fig. 4. Base Cost of 11-Gage Stainless Steel Tubing of Various Types Compared with Carbon Steel (James P. Kelleher)

Because steel may sometimes be affected so adversely during fabrication that it will fail prematurely in service, specimens should be included in the corrosion tests to evaluate proposed fabrication methods. It is advisable to include welded specimens typical of the job, and also sensitized specimens in order to evaluate weld deposit, heat effect in the weld zone, and possible stress-corrosion cracking from residual stresses. Stress-corrosion specimens loaded to various levels of stress should be tested to evaluate susceptibility of the steel to cracking and to indicate whether the fabricated equipment should be stress relieved. Specimens heat treated to represent job conditions should be tested. It is also important that surface finish be typical of the job and the same on all specimens. Frayed surfaces or cold worked edges produced in the preparation of test specimens should be removed before testing.

Careful evaluation of test results is of utmost importance. Microscopic examination of the surface of the specimen for attack at grain boundaries is helpful when corrosion rates are low or available testing time is short. Grain-boundary attack generally indicates poor serviceability.

The subject of corrosion testing and evaluation of test data are described in "Corrosion Testing Procedures", by F. A. Champion (John Wiley and Sons, 1952) and "Corrosion Handbook" (Wiley, 1948).

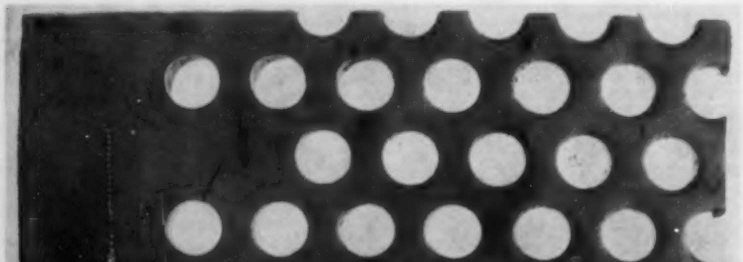


Fig. 3. Stress-Corrosion Cracking in Type 316 after 18-Hr Exposure to Boiling 42% Magnesium Chloride

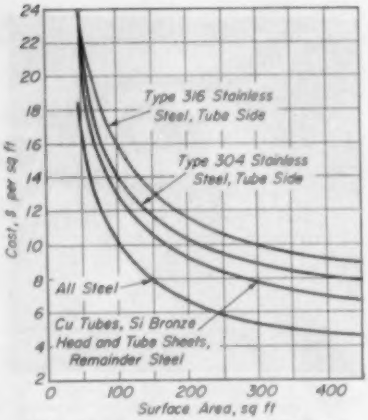


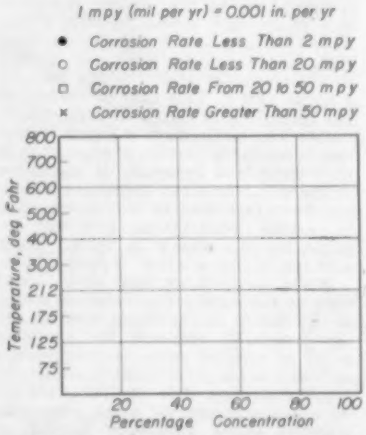
Fig. 5. Cost of Packed-Gland Heat Exchangers with Floating Heads and Removable Bundles (Tube Length, 12 Ft) (A. M. Michell)

Cost

Cost, the basis of engineering practice, enters all problems of steel selection at some point in the analysis, usually at the beginning. The general trend of cost relations between carbon steel and stainless steel is illustrated by Fig. 4 and 5. These show cost trends for tubing, a major item of expense in nearly all chemical plants, and for fully fabricated heat exchangers, another common item. Other forms of stainless steel and the various types of chemical equipment made from it show different magnitudes, but the qualitative comparisons with carbon steel are similar.

Corrosion Data

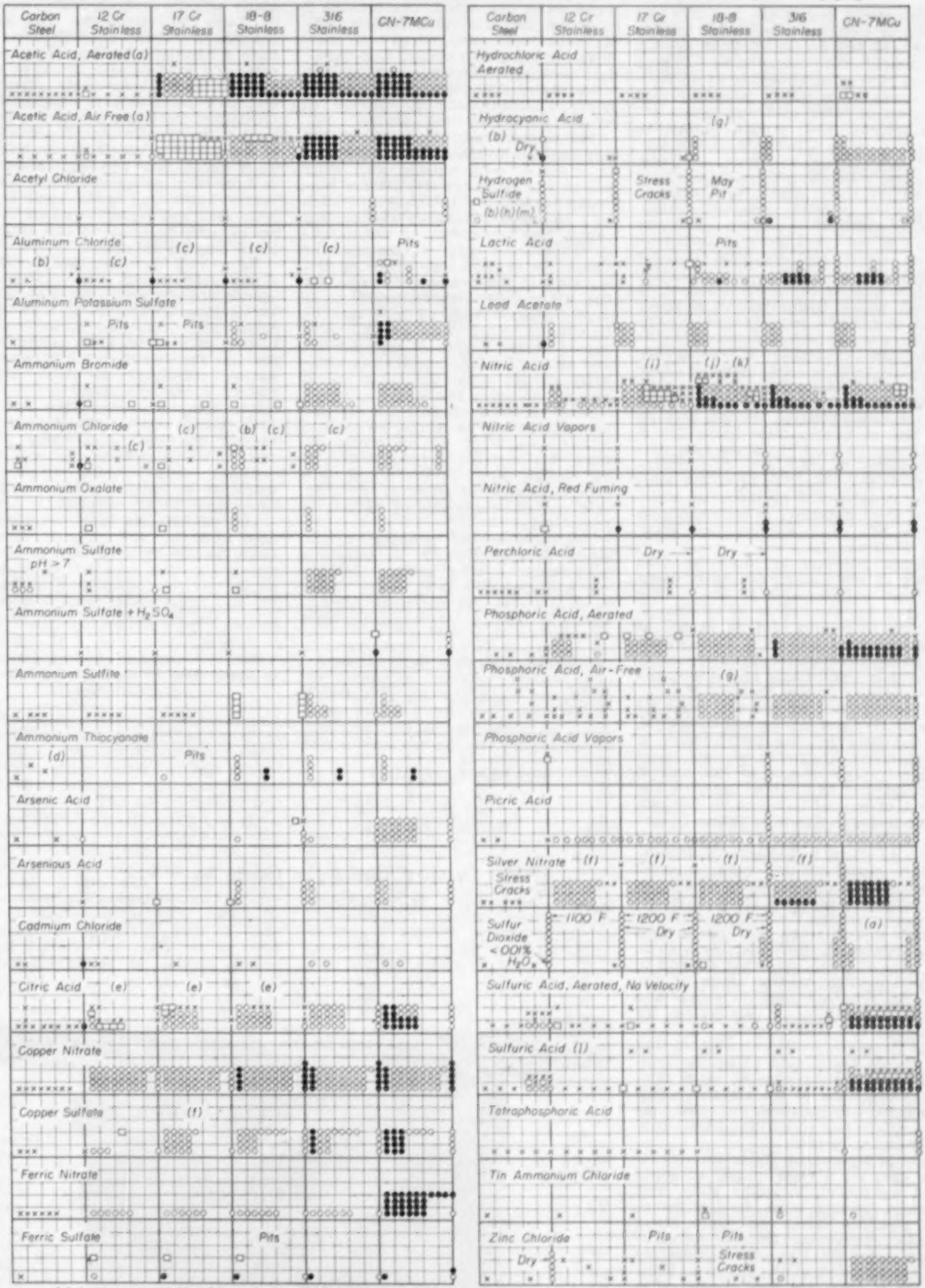
Corrosion data for carbon and stainless steel in contact with each of 40 chemicals are summarized on the next page. Data are omitted for solutions in which carbon steel is satisfactory.



Enlarged Portion of the Unit Graph on Which Corrosion Data Are Presented on the Next Page. The best rating, a solid circle, corresponds to zero or negligible dimensional change during the life of a process. Open circles indicate applications feasible with minor maintenance. Open squares represent applicability for special cases only, not for general plant construction. A cross means the corrosion rate is too high for the combination to be considered.

Corrosion Data for Stainless Steel Compared with Carbon Steel

For explanation of symbols and plotting, see unit graph at bottom of column 3 on the preceding page.



(a) Avoid traces of HCl, H_2SO_4 and NaCl. (b) Stress cracks. (c) Pits. (d) Discolors. (e) Avoid chlorides. (f) Acid free. (g) Intergranular.

(g) Intergranular Corrosion. (h) CO_2-Free. (i) Avoid NaCl. (j) Type 321. (k) Type 347. (l) Air-Free No Velocity. (m) Air-Free.

Compiled from "Corrosion Data Survey", 1954 edition by G. A. Nelson, published by Shell Development Co. Revised by the author to include data available through July 1955. Solutions in which carbon steel serves satisfactorily have been omitted, since such data represent no problem involving selection of stainless steel.

Acetic Acid

Recently, increasing amounts of stainless steel have been used instead of copper and copper alloys in process equipment for acetic acid. Copper alloys have good resistance at all temperatures to the boiling point, provided that air or other oxidizing agents are not present. With process equipment, however, it is difficult to obtain air-free operation at all times; therefore stainless steel, which resists corrosive attack by acetic acid under oxidizing conditions, is being used increasingly.

The straight-chromium stainless steels do not resist corrosion sufficiently in acetic acid solutions and are susceptible to pitting. The austenitic stainless steels are fully resistant to attack by all concentrations of acetic acid at ambient temperatures. As the temperature of the acid increases, the difference in resistance among the stainless types becomes apparent. Type 304 and 347 act similarly in acetic acid. Both show rates of 1.5 mpy or less in all concentrations of refined acid up to 99% at temperatures below 120 F. Both can be used in refined acid concentrations to about 50% at temperatures to the boiling point of the solution. Tests should be made to determine their suitability at concentrations above 50% and temperatures above 120 F (Table III.)

Types 309 and 310 may be used safely in acid concentrations to about 50% at temperatures to the boiling point of the solution or in all concentrations of refined acid up to 99% at temperatures below 170 F. Tests should be made to determine their suitability in acid concentrations above 50% and temperatures greater than 170 F.

The corrosion resistance of types 316 (Table III) and 317, as well as CN-7M, is increased by the molybdenum in these alloys. They may be used in all concentrations of acid to 99% and at temperatures to the boiling point. The effect of ionized halogens on the rate of corrosion is shown in Tables IV and V. These data apply to pure, refined acid; as noted in the preceding paragraph, contaminants — even in small amounts — limit the use of 18-8 types to temperatures below 120 F. Type 317 is more resistant than 316 to corrosive attack in hot acetic acid and is used considerably in distillation equipment, in spite of being somewhat difficult to fabricate. The casting alloys of the CN-7M type are used in pump and valve applications in equipment for handling hot acetic acid.

As the concentration approaches that of glacial acetic acid at boiling temperatures and superheated vapor temperatures, none of the stainless steels are sufficiently resistant. For these concentrations and conditions, nickel-base alloys must be used.

Use of Equipment. Types 304 and 347 are used for a wide variety of acetic acid equipment, including stills, base heaters, holding tanks, heat exchangers, pipelines, valves and pumps, under conditions ranging from dilute solutions (below 50%) at room temperature to concentrated solutions (up to 99%) at 275 F. Type 316, heat treated after fabrication, is suitable for fractionating equipment for acetic acid of 30 to 99% concentration; type 304 is not suitable. Ionized halogens must be eliminated from the solutions. Type 316 is used for storage vessels, pumps, and process piping to handle glacial acetic acid; type 304 is not satisfactory because it discolors the acid. Considerable difficulty has been encountered with castings such as pump volutes and impellers because of contamination by iron from the sand or from abrasive cleaning. Castings should be pickled in nitric-hydrofluoric acid solution.

For temperatures above 120 F and applications involving acetic acid that is mixed or contaminated with other substances, types 316 and 317 are generally satisfactory in equipment such as stills, heat exchangers and holding tanks. The superiority of the molybdenum-bearing types is illustrated by the results of plant tests in boiling 99% acetic acid. The corrosion rates for 304, 321 and 347 varied from 20 to 60 mpy compared with 1.5 mpy for 316. Results of other tests in 99% acid vapors at 230 F gave 63 mpy for 304 and 2.0 mpy for 317. Type 317 has somewhat greater resistance than 316 to severely corrosive conditions.

Alloy castings of type CN-7M are used extensively as pumps, valves and related equipment for all concentrations of acetic acid at temperatures to the boiling point. These alloys have good resistance to mixtures of acetic acid and small amounts of sulfuric or formic acids.

The presence of reducing agents, either as impurities or as necessary constituents in the process, destroys the passivity of stainless steels. Mixtures of acetic acid with other acids — especially sulfuric, hydrochloric and formic — may produce conditions more corrosive than acetic acid itself, particularly at high temperatures. The data in Table VI emphasize that slight changes in solution concentrations can have a significant effect on corrosion rates and that suitable corrosion tests must be made whenever any change in operating conditions is contemplated.

Stainless steels are not always satisfactory for contact with hot solutions of acetic acid of concentrations greater than about 25% and containing 2% or more reducing agent (such as formic acid). If oxidizing agents such as sodium dichromate may be added to the acetic acid, the use of the stainless steels may be extended.

In a still handling boiling 99.5% acetic acid liquors and vapors, the service life of the heating coils of 316 varied from 10 months to 5 yr. Corrosion tests have also shown that in boiling 75% acetic acid vapors, both 304 and 316 were susceptible to severe pitting corrosion. In some boiling liquors where excessively severe corrosive conditions exist (for example, where acetic acid is contaminated with various chlorides) nickel-base alloys such as Hastelloy C have proved more resistant than stainless steels, and their use is justified economically by the longer life of equipment.

The CF-8M cast alloy is generally used with the 18-8 types of wrought steels because its resistance to pitting attack is greater than that of CF-8. To obtain service comparable with that of the 18-8 molybdenum types of wrought alloys, the chromium content of cast

Table III. Corrosion in Acetic Acid

Acetic Acid, %	Temp, deg Fahr	Corrosion, mpy 304	316	347
10	Boiling	<1.5	...	...
25	219	<5.0	<5.0	<5.0
50	Boiling	0.5	0.1	...
70	Boiling	33.0	...	...
75	86	0.1	...	...
75	293	15.8	4.1	...
99.5	284	...	0.2	11.3
99.5	Boiling	27.0	0.9	6.9

Table IV. Effect of Ionized Halogens in Acetic Acid on Corrosion of Type 316 Stainless Steel

Ionized Halogens, ppm	Corrosion, mpy
3.5	7
22.8	30
25.0	37
200	123

At 90% acid concentration and 230 F

Table V. Corrosion in Impure Acetic Acid[a]

Acetic Acid, %	Temperature, deg Fahr	Corrosion, mpy 304	316	316[b]	317	20
10	223	...	2.0	4.0	0.3	4.0
24	230	...	2.7	...	2.7	4.0
83	241	66	9.0	22	4.0	5.0
87	252	42	16.0	...	1.0	8.0
98	262	7.0	2.0	4.0	1.0	2.0
99.5	266	...	0.3	...	0.4	0.5

(a) Data were obtained during processing of acetic acid containing ionized halogens; duration of test, 51 days. Concentration of halide ions varied during period of observation. Concentration estimated as 5 to 10 ppm. (b) Sensitized at 1200 F; all samples were attacked intergranularly.

Table VI. Corrosion in Formic-Acetic Acid Mixtures

Steel	Temperature, deg Fahr	Acid Content, % Acetic	Formic	Corrosion, mpy
304, 347	223	30 to 50	2 to 10	(a)
316	223	30 to 50	2 to 10	3 to 20
317	223	30 to 50	2 to 10	2 to 11
316	200-230	Glacial	0	<1.5
316	200-230	Glacial	4	3.3
316	220	25	1.25	1.5
317	220	25	1.25	<1.0
316	220	25	4	3.0
317	220	25	4	2.0
321, 347	220	25	4	(a)

(a) Completely corroded

alloys should be on the high side of the composition range. Castings should be fully annealed for best service.

Ammonium Sulfate Plus Free Sulfuric Acid

Types 316 and CN-7M are used in this service. Before these steels were available, construction was almost entirely of lead, which was subject to fatigue cracking, and occasionally of silicon iron, which is brittle, thus requiring continuous maintenance. 18% Cr and 18% Cr – 8% Ni steels became pitted and corroded severely.

Type 316 is useful when properly heat treated after welding; otherwise heavy intergranular corrosion occurs adjacent to the welds. When extra-low-carbon stainless steel is used (type 316L) heat treatment is unnecessary and large tanks can be fabricated. Such tanks have been in service for several years with no evidence of either general corrosion or intergranular attack. CF-8M and CN-7M castings heat treated after casting are also useful, although if the casting skin is damaged, corrosion may occur. Castings repaired by welding must be heat treated again after welding; otherwise they will corrode intergranularly adjacent to the welds. Pretreatment of the steel by passivation is not required.

Bromoform

Type 304 generally is satisfactory for handling bromoform, either wet or dry, at ambient temperatures; however, wet bromoform will discolor slightly. If a water-white product is required, stainless steel is not suitable.

Chlorinated Solvents

The halogen derivatives of methane, ethane, ethylene, propane and benzene are widely used in dry cleaning, metal cleaning, vapor degreasing and solvent extraction processes, and as chemical intermediates. The compounds of primary interest are methylene chloride, chloroform, carbon tetrachloride, ethylene dichloride, trichloroethylene, perchloroethylene, methyl chloroform, propylene dichloride, dichloroethyl ether, monochlorobenzene and orthodichlorobenzene. They are used individually as chemically pure or commercial grades, as mixtures, or with other compounds to control boiling point, freezing point, solvency, and flammability of mixtures.

Stainless steels are not corroded by chlorinated solvents when water is absent; but when a water phase is present, the compounds hydrolyze to form hydrochloric acid and sometimes organic acids. Although the presence of metallic materials usually increases the rate of decomposition, stainless steels do not, and their use in equipment for handling chlorinated solvents is generally satisfactory. The corrosion rate of type 304 after 12 days in wet chlorinated solvents at refluxing temperatures is shown in Table VII. These data are from laboratory tests with mixtures of solvent and water, in which one third of the specimen was in the solvent layer, one third in the water layer and one third in the vapor phase.

Table VII. Corrosion of Type 304 After 12 Days in Wet Chlorinated Solvents at Refluxing Temperatures

Solvent	Corrosion, mpy
Methylene chloride.......	0.1
Carbon tetrachloride.......	5.0
Methyl chloroform........	10.0
Trichloroethylene	0.8
Ethylene dichloride.......	0.3
Perchloroethylene	0.1
Propylene dichloride......	17.0

One third of specimen was in solvent layer, one third in water layer, and one third in vapor phase.

Consideration should be given to the use of types 316, 317 or No. 20 for applications where pitting is encountered. Intergranular attack occurs sometimes at welded joints. Tests should be made to determine whether intergranular attack is a problem under the conditions involved. Stress-corrosion cracking may also be encountered in equipment handling chlorinated solvents.

Chlorosulfonic Acid

Although carbon steels are satisfactory for chlorosulfonic acid below the liquid level, type 317 or higher alloys are recommended for withstanding the vapors above and at the liquid level. The products of sulfation, which may retain chlorides, cause stress corrosion and sometimes severe pitting. Pipe welds and vessels of the austenitic steels should be fully annealed whenever this is feasible.

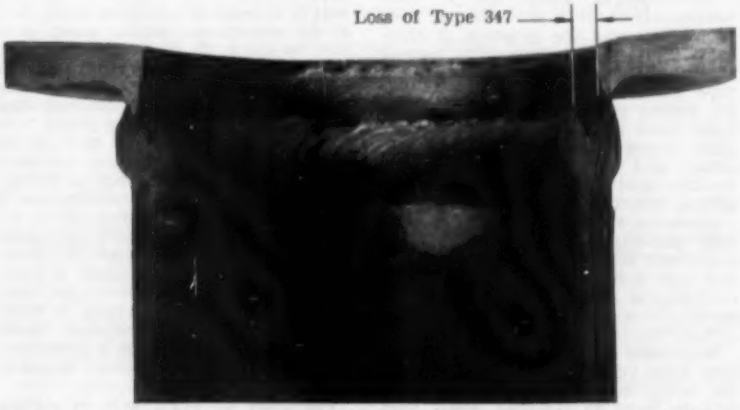


Fig. 6. Weld Metal and Pipe of Type 316 and Flange of Type 347 Corroded by Fatty Acid at 400 F

Epichlorohydrin

Failure in processing equipment by stress-corrosion cracking was confirmed by laboratory tests with horseshoe specimens at 140 F. Types 304, 316 and 347 cracked in a 7-day test.

Fatty Acids

The fatty acids of lower molecular weight, such as acetic and formic, require the use of 18-8 stainless steels (see section on Acetic Acid.) The following discussion is concerned with the acids of higher molecular weight, such as lauric, myristic, palmitic, and stearic, which are less corrosive. At temperatures to 150 F, cheaper metals such as carbon steel and aluminum are moderately corroded, but if color and absence of contamination of the product are important, the 18-8 steels should be used.

If the temperature is below 350 F, all standard 18-8 types are satisfactory; above 350 F, type 316 is needed to avoid pitting corrosion.

Corrosion in fatty acid vapors is no greater than in liquid, except at high vapor velocities. Under these conditions corrosion-erosion rates have been lower in type 316 than in types 304, 321 and 347.

Table VIII. Corrosion in Fatty Acids Acidulated with Sulfuric Acid

(Steam Agitation)

Sulfuric Acid, %		Temp, °F	Corrosion, mpy	
			304	316
0.01	....	205	15.4	6.0
0.1	....	225	7.55	3.8
5.0	....	200	48.0	19.2
10	....	215	...	77.5
25	....	240	...	467

Pitting and loss of surface metal are caused by high-temperature plant processes (Fig. 6). There are no reports of straight fatty acids having caused intergranular failures in 18-8 stainless steels.

Cast alloys, including type CN-7M, have been satisfactory. The molybdenum-bearing wrought steels and the newer precipitation-hardening stainless steels have been used for pump and valve parts where galling is a factor or where hardness of parts is desirable. High-nickel cast iron has given satisfactory service in fatty acid at 500 F.

Fatty acids mixed with chlorides cause failures by stress-corrosion cracking (Fig. 7). Acidulation of fatty acids by sulfuric acid produces a wide variation in corrosion rates of stainless steels. Factors that contribute to such variation include unknown dilution of the concentrated sulfuric acid, the moisture inherent in the fatty acids, temperature and methods of agitation. Corrosion rates encountered with acidulated fatty acids of higher molecular weight with steam agitation are reported in Table VIII.

Hydrochloric Acid (Dilute)

Although types 316, 317, 329 and No. 20, and the cast alloys CN-7M and CF-8M find some use in very dilute aerated hydrochloric acid environments, stainless steels are not usually recommended for this service.

Solutions containing chloride salts at pH below 7.0 are essentially hydrochloric acid environments. Pitting and stress-corrosion cracking are encountered at acid concentrations less than 1%, depending on the temperature, aeration and agitation.

Bimetallic couples between stainless and other alloys should be avoided, since corrosion may be accelerated at their junction. In such couples the stainless steel may become the anode in dilute hydrochloric acid, resulting in loss of passivity and rapid corrosion.

Corrosion Failures. Hydrochloric acid at pH 2.0 to 4.0 and 120 to 180 F has caused pitting and subsequent failure of heat-exchanger tubing and heating coils. Calcareous scale has induced pitting failures. Activated carbon that settled out has caused pitting of heating coils and tank bottoms (type 316).

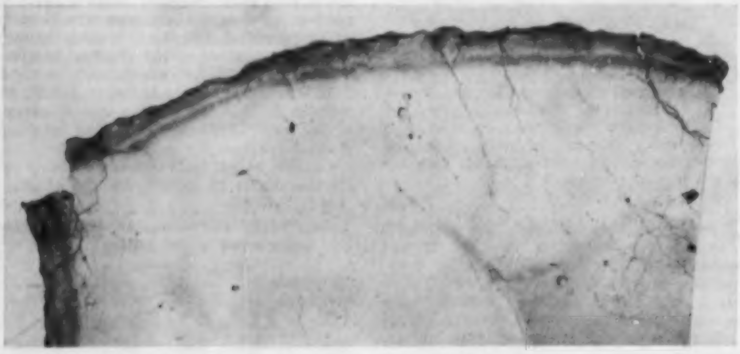


Fig. 7. Stress-Corrosion Cracking Caused in Type 304 by Citric Acid and Salt at 212 F

Stress-corrosion cracking of heat-exchanger tubes has occurred at pH 4.0 and 160 F. Excessive stresses were induced in the tubes when a floating head on the heat exchanger became "fixed". Bending of tubes between baffle supports has induced stress-corrosion cracking of tubes of 316 stainless steel. Excessive rolling of tubes into the tube sheets has induced stress-corrosion cracking of the tubes just adjacent to the sheets.

Weld deposits of type 316 on sheet of similar grade have corroded, weakening the joint. Weld deposits using an electrode of type 317 or 310-Mo have improved the corrosion resistance of these welds. Weld-zone attack has been observed in type 316 linings for steel tanks handling acidified starch slurry at pH 2.0 and 120 F.

Covers and vents from acidified starch slurry tanks usually corrode rapidly. Condensed vapors of dilute hydrochloric acid environments are usually more corrosive than the liquid phase. Stainless steels are usually unsatisfactory for tank covers or vent piping for such tanks.

Hydrocyanic Acid

Pure hydrocyanic acid is not corrosive to most materials of construction, but when stabilized against polymerization at elevated temperature by the addition of acidic materials, it becomes corrosive to steel, copper and aluminum. The straight-chromium stainless steels are not recommended for use with stabilized hydrocyanic acid solutions.

The austenitic stainless steels resist corrosion by hydrocyanic acid that contains small amounts of sulfur dioxide as a polymerization inhibitor, at all concentrations and temperatures to the boiling point. Types 316 and 317, as well as CN-7M and CF-8M, have greater corrosion resistance than the stainless steels without molybdenum. The unstabilized stainless steels should be fully annealed to prevent intergranular attack in these solutions.

Lactic Acid

Types 304, 316, 317, No. 20, CN-7M and CF-8M have limited use in lactic acid solutions. The molybdenum-containing varieties generally have greater corrosion resistance than type 304.

Purity, concentration, temperature, aeration and agitation are environmental factors that determine the type of stainless steel for use in process equipment. The presence of chlorides or sulfates in lactic acid solutions increases the severity of corrosion. Impure solutions from which lactic acid is ultimately separated and concentrated are usually more corrosive than the purified solutions. Stainless steels are not suitable for use with lactic acid above 200 F.

Heating coils or heat exchangers for lactic acid should be designed for use with hot water or low-pressure steam. Decomposition of lactic acid with formation of carbonaceous deposits on heating coils can result in pitting and perforation under these deposits.

Temperatures above 200 F, concentrations of lactic acid ranging from 30 to 70%, and the presence of chlorides or inorganic impurities usually increase severity of corrosion. Use for type 304 should be limited to vessels for storing pure solutions at temperatures below 100 F. Distillation of lactic acid causes corrosion by the vapor phase, and if lactic acid esters and volatile acid impurities are present, pitting attack will result.

Corrosion Failures. Pitting failures in heat exchangers for lactic acid solutions have been reported. One failure of this type was limited to surfaces covered by the liquid, particularly in the parts of the tubing where solids have settled out.

Weld-zone attack and corrosion failures have been reported for type 304, but rarely for type 316. The weld-zone failures were in stainless steels that were not of the extra-low carbon variety and had not been annealed.

Monoethanolamine

Stainless steels have excellent resistance to corrosion by monoethanolamine and by monoethanolamine saturated with carbon dioxide plus oxygen at temperatures to 200 F. Stainless steel is used in preference to carbon steel in process steps where carbon dioxide is stripped from monoethanolamine — for example, in reboilers, exchangers and parts of fractionating columns. For heat exchangers, a common practice is to specify stainless steel only for tube bundles having 150-psi steam inside and monoethanolamine that is rich in carbon dioxide outside. Type 304 is adequate.

Experience has been variable with stainless steel in monoethanolamine solutions as used in processes for removing hydrogen sulfide or carbon dioxide from natural and refinery gases. Probably about one fourth of the amine gas treating plants make some use of stainless steel piping and vessels. Remedial process changes can often be devised to avoid the use of stainless.

Nitric Acid

Stainless steels, first used commercially on a large scale in service involving nitric acid, continue to be used in such installations. These first applications were of 15 to 18% Cr steel (now type 430) and soon thereafter of 18% Cr – 8% Ni steel (now type 304). The necessity for proper heat treatment to prevent accelerated corrosion and intergranular attack in nitric acid was demonstrated at once through service failures of improperly heat treated and as-welded equipment. These difficulties were eliminated by postfabrication heat treatments involving slow cooling from about 1450 F for type 430, and rapid cooling from about 2000 F for type 304. Subsequently, for the austenitic grades, the use of stabilizing elements (particularly columbium in type 347) and more recently reduction of carbon content to 0.03% max (type 304L) have been effective in controlling this problem without the necessity for quenching fabricated equipment from a high-temperature heat treatment. In the as-welded condition, 304L and 347 show satisfactory resistance to corrosion by nitric acid and are therefore suitable for field-erected equipment.

Where corrosion rates on equipment must be held to less than 5 mpy, types 304L and 347 can be used with nitric acid in concentrations up to about 40%, at the atmospheric boiling point; 40 to 70%, to about 175 F; and 70 to 90%, to about 120 F. For a corrosion rate of 50 mpy max, the corresponding limits are approximately 40 to 70% concentration of nitric acid at the boiling point; 70 to 90% at 160 F, and 90% at 85 F. If the acid is recirculated so that corrosion products accumulate, attack in hot solutions at the higher concentrations is accelerated when the chromium in the acid exceeds a certain level. With boiling 65% nitric acid, the limiting chromium content of the solution is about 0.005%, above which corrosion increases rapidly with further increases of chromium in the nitric acid solution. Under these conditions, corrosion is intergranular, even with the stabilized or extra-low-carbon grades.

Corrosion by nitric acid in storage is slight for concentrations to about 94%, but the acid condensate is of higher concentration, and attack becomes appreciable on the part of the tank exposed to the condensate (Table III). (Aluminum is commonly used for storing 95 and 98% nitric acid, but its resistance decreases rapidly with decreasing concentration; consequently, exposure to the dilute acid must be avoided.) Corrosion data for specimens of 347 and 430 steels for various concentrations of nitric acid at 72 F are compared in Table IX. In hot concentrated solutions where attack is too severe to be tolerated, high-silicon iron can be used if its mechanical properties are suitable.

In reactions under pressure and at temperatures considerably above the atmospheric boiling point, corrosion rates of all the stainless steels increase rapidly with both temperature and concentration; under these conditions, only very dilute nitric acid solutions can be handled suitably in equipment made of stainless steel.

Type 304 in the annealed and water-quenched condition has essentially the same resistance to corrosion by nitric acid as types 304L and 347, but type 304 should be heat treated after fabrication to prevent intergranular corrosion. Types 316 and 316L in the annealed condition are about the same in resistance to nitric acid, but unless these types are required for reasons other than resistance to corrosion, their use is usually not justified because of higher cost.

The type 309-Cb is somewhat more resistant under the most severe conditions and is occasionally used where the lower-alloy stainless steels are not quite satisfactory. If properly annealed and water quenched, types 309 and 310 have about the same resistance as type 309-Cb. However, unless their carbon content is less than about 0.10%, these alloys cannot be cooled fast enough in commercial heat treatments to avoid susceptibility to intergranular corrosion. Since types 309 and 310 are employed principally for resistance to scaling at elevated temperature and are usually of higher carbon content, they are seldom used in equipment for service with nitric acid.

Typical corrosion rates of annealed austenitic stainless steels in boiling 65% nitric acid are given in Table X.

Type 430 is still widely used for various kinds of equipment in the ammonia oxidation process for nitric acid manufacture, and for tank cars, storage tanks, forged valves and other components. It costs less than the austenitic grades and, while temperature ranges are somewhat more limited for various concentrations, this alloy is adequate for many applications. Its principal limitation is that it requires heat treatment after fabrication and is therefore not suitable for equipment erected in the field or for repair of equipment. Limits of nitric acid concentration for a maximum corrosion rate of 5 mpy are as high as about 20% at the atmospheric boiling point; 20 to 40%, to about 160 F; 40 to 70%, to about 140 F; and 70 to 90%, to 85 F. Corresponding limits for not more than 50 mpy are approximately 20 to 40% concentration of nitric acid at the boiling point; 40 to 70%, to 195 F; 70 to 90%, to 120 F; more than 90%, to 85 F.

The resistance of chromium steels to nitric acid is related directly to the chromium content, as indicated by the data in Table XI for tests in boiling 65% nitric acid.

Type 446 is comparable to type 304 in resistance to nitric acid, but because it is more difficult to fabricate, it is employed in only a few special applications. With the exception of type 430, none of the other chromium steels are used to any appreciable extent in contact with nitric acid.

The stainless steels are relatively insensitive to factors such as aeration, velocity and agitation, since nitric acid is oxidizing and tends to favor passivity. Neither pitting nor stress-corrosion cracking is a problem under these circumstances. However, nitric acid causes intergranular attack in unstabilized stainless steels that contain more than 0.03% C, unless they have been properly heat treated. The presence of hydrofluoric acid in nitric acid, as in certain pickling solutions, increases such attack. Hydrofluoric acid also increases the rate of general corrosion, as do appreciable amounts of other halides.

In hot dilute mixtures of nitric and sulfuric acids, no appreciable attack occurs on the stainless steels when the ratio of nitric acid to sulfuric acid is about 2 to 1 or higher. This is one of a number of examples where sufficient nitric acid will prevent attack that would otherwise occur. With very dilute hot mixtures of sulfuric acid and nitric acid (about 1 to 1.5% total acid), where the proportion of nitric acid is not sufficient to maintain passivity for the austenitic grades, type 443 (20% Cr, 1% Cu) has greater resistance.

Table IX. Corrosion of Steels Commonly Used with Nitric Acid

Nitric Acid, %	Corrosion at 72 F, mpy			
	Type 347		Type 430	
	Liquid	Vapor	Liquid	Vapor
98.5	61.0	47.0	67.0	51.0
96.3	16.0	38.0	20.0	42.0
94.2	2.3	30.0	4.6	29.0
92.6	0.1	28.0	1.1	27.0
90.1	0.1	7.0	0.6	27.0
85.1	0.1	0.1	0.4	0.1

Table X. Corrosion in Boiling 65% Nitric Acid

AISI Type	Corrosion, mpy
304	7.0
304L	7.0
309	4.0
310	4.0
316	8.0
347	7.0

For annealed steels

Table XI. Corrosion of Chromium Steels in Boiling 65% Nitric Acid

Chromium, %	Corrosion, mpy
10	420.0
12	180.0
16	40.0
18	26.0
20	18.0
24	12.0
26	7.0

Castings. Corresponding cast grades (CF-8, CF-8M and CN-7MCu) are widely used for valves, pumps and other castings in nitric acid service. Addition of stabilizing elements (usually columbium) or restriction of carbon content to 0.03% is not ordinarily justified, since most stainless castings can be quenched readily in water, and they are seldom welded in place in the field. Types CF-8M and CN-7M, containing molybdenum or molybdenum and copper, are no more resistant to nitric acid than the CF-8 (18-8) grade but will handle a wider variety of process solutions. High molybdenum (and silicon) contents are somewhat detrimental to resistance to hot nitric acid in intermediate and higher concentrations. Cast chromium stainless steels are seldom used in nitric acid service.

Phosphoric Acid

The resistance to corrosion by phosphoric acid solutions is similar to resistance to sulfuric acid solutions, but the allowable ranges of concentration and temperatures for acceptable performance are somewhat greater for phosphoric than for sulfuric acid.

Type 304 stainless steel has been satisfactory for handling dilute aqueous solutions of phosphoric acid at pH 3 and room temperature, except where filter-aid or carbon or both are present, in which instances pump impellers have failed after 4 to 6 weeks of continuous service. The failures were attributed to a combination of corrosion and abrasion. Tanks and pipe lines handling the same material gave satisfactory service for more than 5 yr.

Silver Nitrate

In the production of silver nitrate where contamination must be held to a minimum, corrosion cannot exceed 1 mpy. Type 310 and a modified 309, in which the chromium content is 24% min, meet this requirement. Types 304 and 316 are suitable for aqueous solutions of silver nitrate at room temperature, but are unsatisfactory at elevated temperatures or for acidified solutions. This is illustrated by an installation in which a CF-8M casting was used for valve bodies, mixer shafts and blades in equipment that handles, at room temperature, a 70% silver nitrate solution containing traces of nitric acid. After 15-yr service the equipment was still in excellent condition; however, when valve bodies of this composition were used in 85% silver nitrate solutions at 200 F, corrosion failure resulted in 3 yr.

Type 310, CK-20 or the modified 309 or CH-10 (24% Cr min) should be used for elevated temperatures and in acidified solutions as encountered in the production of silver nitrate from nitric acid and silver.

Cast alloys corrode more readily than wrought alloys. This is attributed to the lower corrosion resistance of the ferrite in castings, especially in CH-10. Service is satisfactory with CK-20.

Use of Equipment. Correct annealing and pickling are necessary to hold the corrosion to 1 mpy. In a unit for the production of silver nitrate crystals, dissolving-kettles fabricated from properly annealed and pickled 309 with

Table XII. Corrosion by Some Solutions of Inorganic Compounds

Compound and % Concentration	Steel	Temperature, deg Fahr	Corrosion, mpy
30 Ammonium Arsenate	304	Boiling	5
10 Ammonium Chloride	316	Boiling	<1
0.4 Hydrochloric Acid	304	80	10
0.4 Hydrochloric Acid	316	120	5
30 Manganese Chloride	304	194	0.7
30 Manganese Chloride	347	194	0.7
28 Nickel Sulfate	304	122	0.04
40 Sodium Bisulfide	304	Boiling	1.6
40 Sodium Bisulfide	316	Boiling	1.1
30 Sodium Sulfide	304	130	0.1
30 Sodium Sulfide	316	130	21
40 Sodium Sulfide	304	Boiling	1.5
40 Sodium Sulfide	316	Boiling	2.5
6 Sulfurous Acid	304	104	0.1
6 Sulfurous Acid	304	194	18
100 Sulfur Chloride	304	Boiling	1.3
100 Sulfur Chloride	410	......	3.1

All steels in the annealed condition. All solutions from CP chemicals. Tests made in the laboratory

chromium content greater than 24%, are still in excellent condition after 20 yr. Similar kettles installed at the same time, having less than 24% Cr, lasted 6 yr. These kettles handle solutions varying from 0 to 85% silver nitrate and from traces to 50% nitric acid at 200 F.

As indicated above, there are several variations which may affect the low corrosion rates required of stainless steels in silver nitrate solutions. Since the total of these effects cannot be determined simply by chemical analysis of the steel, corrosion tests should be run for each heat of stainless steel before fabrication, regardless of composition, for silver nitrate applications.

Sodium Sulfide

Type 304 can be used satisfactorily in contact with sodium sulfide solutions up to 50% concentration and to the boiling temperature of the solutions (Table XII).

In repairing equipment that has been in sulfide service, the surface should be cleaned thoroughly by abrasive blasting before welding, to avoid cracking during welding.

Stannic Chloride

Types 304 and 316 have satisfactory resistance to aqueous solutions of stannic chloride at temperatures to 200 F for concentrations not exceeding 1%. Type 316 is more resistant than 304 and has fair resistance to solutions of 10 to 15% at 70 F, but its resistance is unsatisfactory at higher temperatures and concentrations.

Stannous Fluoride

Laboratory tests made at 200 F with aqueous solutions ranging from 2 to 50% by weight indicate that stannous fluoride solutions can be handled in equipment made of the 300 series stainless steels. A maximum rate of 3.9 mpy was obtained in a 2% solution. With allowance for experimental error, all rates either decreased or remained the same with increasing concentrations. No tendency toward pitting could be found, and stressed horseshoe-type specimens of 304 and 316 tested for stress-corrosion cracking did not fail. Table XIII gives a summary of these corrosion tests.

Table XIII. Corrosion by Stannous Fluoride

Solution Strength, Wt %	Corrosion, mpy 304	316	347
2.0	3.92	...	...
15	0.9	None	0.39
30	0.56	None	0.79
50	1.81(a)	...	...

(a) Stained black

Sulfation and Sulfonation Products

The austenitic stainless steels and carbon steels have low corrosion rates in oleum (fuming sulfuric) and sulfuric acid of more than 80% concentration at room temperature. At 100 to 103% there is a distinct rise in the corrosion rate with carbon steel. Above 103%, both stainless and carbon steels have satisfactory corrosion rates. Steels of the 300 series are satisfactory for sulfonation practice at room temperature with 78% sulfuric acid mixed with sulfonation products. At 140 F corrosion of series 300 steels is excessive. Corrosion rates at these temperatures are reported in Tables XIV and XV.

Table XIV. Corrosion by 78% Sulfuric Acid Mixed with Sulfonation Products

Alloy	Corrosion, mpy 80 F	140 F
Type 316	0.2	20
Hastelloy B...........	...	0.6
Hastelloy C...........	...	1.5
No. 20.................	None	3.0
Inconel	None	8.0
Mild steel	20	134

Table XV. Corrosion by Spent Sulfuric Acid After Separation of Sulfonation Products

Alloy	Corrosion, mpy 80 F	140 F
Type 316	0.21	15.12
No. 20	0.06	5.94
Inconel	0.09	19.35
Mild steel	18.9	63.6

If accuracy of parts is essential, as in valves and control instruments, or if velocity of liquid is high, as in pumps or mixing operations, corrosion rates are excessive, and steels such as CN-7M and nickel-base alloys are needed. The neutralized products of sulfonation may separate when stagnant, and the series 300 steels can be severely pitted by the resulting diluted acid.

Sulfuric Acid

The 18-8 varieties of stainless steel are resistant to corrosive attack by sulfuric acid within rather narrow ranges of concentration and temperature.

Although the stainless steels may be used safely in contact with 80 to 100% sulfuric acid at ambient temperatures (carbon steel is ordinarily used in this range), they are attacked at slightly higher temperatures. One to 5% sulfuric acid at ambient temperature should not be stored in vessels of molybdenum-free stainless steels. Type 316 may be used for this purpose; 317, with a higher molybdenum content, may be used safely in this range of acid concentration at temperatures as high as 150 F.

Alloys such as No. 20 and CN-7M resist all concentrations of sulfuric acid at temperatures to 140 F, and to the boiling point for concentrations to 10%, but do not resist all concentrations over a wide range of temperatures.

The preceding data pertain to pure sulfuric acid. The addition of oxidizing agents (such as nitric acid, air and copper salts) will widen the range of applicability of all stainless steels; reducing agents (such as hydrogen) will narrow the range of usefulness. If other than pure sulfuric acid is used with stainless steel, corrosion tests must be made under conditions of operation in order to evaluate the usefulness of the alloys.

Only those concentrations of sulfuric acid and temperatures should be used that have given satisfactory results in corrosion tests. Tests should include annealed, sensitized (1200 F for 8 hr), stressed and crevice-type specimens.

Agitation and aeration in stainless steel equipment and the velocities of sulfuric acid solutions in piping should be adequate (5 to 15 fps) to keep all solids suspended. Charring of organic matter or deposition of scale (such as calcium sulfate) may result in pitting and perforation. The surfaces should be kept clean during shutdown periods.

Corrosion Failures. Organic acids and traces of inorganic salts contributed to the corrosion failure of welded zones in a steam-jacketed kettle of type 316 used to heat 4% sulfuric acid in methanol. The interior surfaces of the kettle are shown in Fig. 8. This failure could have been avoided or delayed by the use of 316L or by fully annealing the kettle after fabrication.

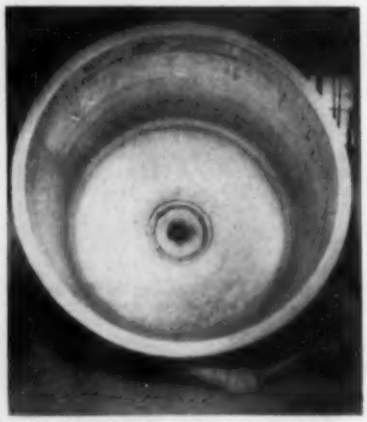


Fig. 8. Weld-Zone Failures in Jacketed Kettle of Type 316 Stainless after 1½-Yr Service in Methanol with Dilute Sulfuric Acid

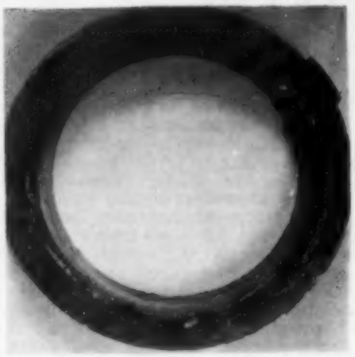


Fig. 9. Flange of Van Stone End of Type 316 Pitted by Sugar and Sulfuric Acid at pH 1.8 and 275 to 325 F

The corrosion failure of Van Stone ends (type 316) on a continuous converter for sugar solutions is shown in Fig. 9. Crevice-type corrosion in the flanged ends was increased by a carbonaceous deposit at these points. The solution contained sulfuric acid at pH 1.8 and was held between 275 and 325 F. Since the ends had not been annealed after forming, corrosion was increased by the severe stresses developed in the flanged areas. The corrosion could have been curtailed by using ends with a thicker wall and annealing, and by cleaning the carbonaceous deposit.

Sulfurous Acid and Sulfur Dioxide

Stainless No. 20, types 316, CF-8M, 317 and CN-7M have been used in equipment for sulfur dioxide (wet) and sulfurous acid environments. The molybdenum in these alloys gives the required resistance to reducing environments of sulfurous acid. The wrought type 316 and cast CF-8M alloys are the most widely used.

Complete suspension of any solids present is necessary to avoid crevice-type pitting. Figure 10 shows pitting and perforation of a Van Stone flanged end of 304 stainless welded to a tube of type 316; the latter did not corrode. Crevice pockets, lapped joints, 90-deg corner intersections and similar obstructions should be avoided, and the surfaces should be clean and smooth.

Cold and hot working should be limited to minor forming operations that will keep the hardness of the steel below Rockwell B 96. Stress-corrosion cracking can occur in steel exposed to sulfurous acid solutions containing 100 ppm or more of metal chlorides.

To insure against failure of weld zones in severe environments (more than 1.0% sulfur dioxide) extra-low-carbon alloys should be used for equipment that requires much welding.

Corrosion Failures. Crevice-type pitting has caused the failure of tank bottoms and perforation of heating coils. Solids, such as filter-aid, activated carbon and bentonite, which settle on the bottom of tanks and the top of heating coils, cause pitting and perforation of these surfaces.

Tubing of type 316, handling sulfur dioxide and sulfur trioxide vapors between a sulfur burner and a sulfurous acid absorber, experienced accelerated corrosion caused by condensation of moist sulfurous acid and sulfuric acid at 150 to 250 F. A field corrosion test had indicated that stainless steels were unsatisfactory for this environment.

Severe erosion-corrosion of pump impellers and valve bodies has been caused by sulfurous acid slurries that contain suspended solids. Pump impellers may fail from erosion-corrosion in a few weeks. Alloys such as types 316, CF-8M and CN-7M generally give the longest service in erosion-corrosion environments. The useful service life of the stainless steels can be predicted from data obtained in a laboratory corrosion test of circular specimens, centered on a stainless steel shaft revolving at high speed (10,000 rpm) in the process slurry.

Fine and Pharmaceutical Chemicals

Stainless steels, principally the 18-8 type, are used by the fine chemical and pharmaceutical industry for maintaining sanitary conditions in corrosive and noncorrosive environments, as well as for resistance to corrosion. Considerations of sanitation dictate the selection of stainless steels for the majority of installations. Although the corrosion resistance of the equipment handling the product is important, the effect of corrosion on the life of the equipment is usually less important than the effect of corrosion products on the chemicals or biologicals being processed.

The purity, color and stability of the pharmaceutical products may be greatly affected by the presence of trace quantities of metallic ions. For example, traces of iron affect vitamin B_1 by forming a highly colored complex; therefore stainless steel is unsuitable for handling vitamin B_1 hydrochloride even at very low corrosion rates. Stainless steel has proved satisfactory for the processing of vitamin C, but all traces of copper must be eliminated, since copper in aqueous solutions accelerates the rate of decomposition by a factor of about 3000.

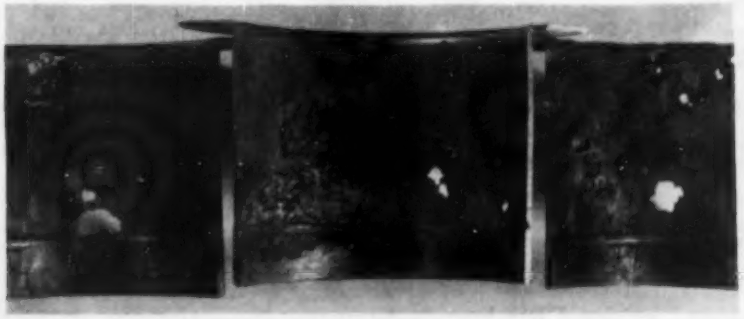


Fig. 10. Van Stone Flange of Type 304 That Was Pitted and Perforated by Sulfurous Acid. The type 316 tubing to which it was welded was not corroded.

Although carbon steel is satisfactory for handling dry chloroform at room temperature, it will not serve in processing operations involving chloroform that contains acid. Where a carbon steel pipeline was used with a chloroform processing system made of type 316 stainless steel, it was found necessary to install type 316 pipe.

A carbon steel pipe that carried the solution from the condensation reaction unit, which contained a free base neutralized with hydrochloric acid at pH 5.8, gave satisfactory service until a process at pH 5.0 was initiated. Then corrosion immediately became noticeable. Stainless steel pipe (type 20), installed as a replacement, gave satisfactory service although some corrosion still occurred. Generally, type 20 can be used with solutions acidified with hydrochloric acid above pH 5.0.

A complex of metaphosphates called "hyphos" has been used as a chelating agent. In an emergency, the solution was transferred in a pipe of carbon steel. After a short time the pipe had corroded wafer thin. Replacement with type 316 showed no corrosion.

Among the various fine and pharmaceutical chemicals handled in stainless steel equipment are: 35% ammonium sulfate (pH 4 to 7.5), 5% butanol at 70 F, 25% caustic at 70 F, 20% phenol at 70 F, 20% sodium sulfite at 80 F, 50% sodium hydroxide, organic acids from protein extraction (pH not less than 4.5), and biological mediums.

Uses in the Pulp and Paper Industry

The use of stainless steels in the pulp and paper industry is not confined to solving corrosion problems. Stainless steels are often selected because they resist scaling and sliming, prevent contamination, and have good mechanical and physical properties. There are two pulpmaking processes—one utilizes mechanical or ground wood pulp and the other, chemical pulp. This section is devoted to chemical pulping by the alkaline process, which is the one more widely used in the production of pulp for papermaking. The process comprises the soda and sulfate method of separating wood fibers from lignin by digesting the wood chips in a large pressure vessel (the digester) with a solution of sodium hydroxide - sodium sulfide and steam. Other chemicals that may be present are sodium carbonate, sodium sulfate, sodium sulfite, sodium thiosulfate, sodium silicate and sodium polysulfides.

During recent years corrosion problems in alkaline digesters have caused much concern and investigation. Five years ago, the Technical Association of the Pulp and Paper Industry (TAPPI) formed a subcommittee to study the problem. A great number of reports, data sheets and technical papers on the subject have been presented to the industry and, through the combined efforts of the committee, a report on the inspection of digesters was prepared. It is believed that by applying the recommendations made in the report (TAPPI Monograph 12, 1954), corrosion in digesters can be mitigated.

The committee reports that for 86 carbon steel digesters, the average corrosion rate was 28 mpy, while for 13 alloy digesters (stainless and high-nickel alloys) the average was 7 mpy. It was estimated that the annual cost to the U.S. industry for this deterioration from alkaline corrosion is $2 million, or 22c per ton of pulp. It would seem that, unless the corrosion is well above average in any one particular plant, the continued use of carbon steels for digester fabrication is still economically justifiable.

To combat severe corrosion, a few users have installed clad or lined digesters in their mills. Types 347 and 316L have been used for this purpose, as either clad or applied linings. Inconel has also been used with good success except where field strip linings have been applied directly on the carbon steel. Type 347 stainless steels have shown the greatest general attack in the vapor portion of the digester.

In the liquid portion of the digester, the alloys show very little general corrosion but some applied linings of stainless steel have stress-corrosion cracked. This has been caused largely by leaks at the seal welds which have allowed liquor to penetrate into the crevice between carbon steel and liner where it can become concentrated by removal of the moisture. The end result is a concentration of salts in the liquor which, together with elastic stresses in the stainless steel lining, causes stress-corrosion cracking from the back side and also undermines austenitic stainless steel seam welds from the carbon steel, thus removing the attachment of applied liners.

A successful method for combating the penetration of liquor behind applied linings is the steam back-pressuring of all of the lining in the digester. This prevents leaks from concentrating and prevents stress-corrosion cracking.

After the pulp has been washed and separated from the liquor, the shives, dirt and fiber bundles are screened. Corrosion and the maintenance of cleanliness were an unending problem in this operation until stainless steels were employed. In general, stainless steels are becoming more widely accepted as one of the most satisfactory materials for alkaline pulping equipment where corrosion is a problem.

Except for a few applications, the stainless steels have not been satisfactory in equipment for the bleaching operation because of the high concentration of chlorides required in this process. Washer-faces of type 316 have given good service in the last stage of washing.

In the papermaking cycle the problems of corrosion are much less serious than in the pulping or bleaching cycles. Stainless steels are being accepted widely because of the cleanliness that must be maintained to meet the requirements for fine papers and for other reasons given at the beginning of this section.

Tables XVI and XVII are reports of experience with stainless steels in an alkaline sulfate mill. The tabulations follow the sequence of operations in the manufacture of pulp and paper. It should not be assumed that because the particular application of a certain alloy was successful in one plant, it would be the answer to a corrosion problem in another similar mill.

Kraft digesters that were lined with type 316 and 347 failed from stress corrosion caused by concentration of liquors that had leaked under the liners. It is not unusual to find sodium chloride present in the niter cake used to prepare the white liquors for the Kraft process. However, after experiencing some of this cracking in service, one firm made up synthetic solutions of commercial white liquors from chemicals which, according to the manufacturer, did not show any more than the following amounts of chlorine:

Na_2S	0.005% Cl
Na_2SO_4	0.001
NaOH	0.000
Na_2CO_3	0.001

Results of tests with these salts showed that cracking requires higher concentration when a single salt is used; for instance, 116 g of Na_2S in water to make 500 ml did not crack type 347 in 96 hr at 360 F; 263 g of Na_2S cracked type 347 in 136 hr; 200 g of NaOH cracked type 347 in 120 hr.

Table XVI. Experience with Stainless Steels in the Unbleached Pulping Cycle

Application	Reasons for Selection	Alloy Type	Environment	Serviceability
		Wood Room		
Pond circulation pump	Corrosion resistance	302	Condenser water from evaporator process	Very good
		Digester Room (Sulfate Process)		
Pulp sampling tables and sinks	Corrosion resistance, cleanliness	304	Kraft unwashed pulp	Excellent
Digester steam nozzle ring	Corrosion resistance, and wearability	304 and 316	Wood chips, black and white liquor, steam	Good Excellent
Digester relief piping	Corrosion resistance, wearability	304	Gases from digester	Good
Blow-heat condenser tubes	Cleanliness, corrosion resistance, heat transfer	304	Gases and vapor from digester blow	Excellent
Digester blow valves	Corrosion resistance, wearability	304	Cooked sulfate pulp	Good
Turpentine recovery condenser	Cleanliness, corrosion resistance, heat transfer	304	Initial gases and vapors at beginning of cooking	Excellent
		Pulp Washing (Sulfate Process)		
Blow-tank target	Corrosion and erosion resistance	316	Cooked (unwashed) pulp	Good
Knotter screens	Corrosion resistance, cleanliness	304	Pulp and black liquor	Good
Knotter conveyor and storage tank	Corrosion resistance	304	Uncooked knots and black liquor	Good
Wire cloth on washers	Corrosion resistance	304	Kraft pulp	Good
Pulp conveyor	Corrosion resistance, cleanliness	304	Washed unscreened pulp	Excellent
Fastenings and accessories	Corrosion resistance	304	Corrosion atmosphere	Excellent
Filtrate pumps	Corrosion resistance	20 Ni, 2 Cr, 1.75 Si	Black liquor dilute	Excellent
		Recovery		
Evaporator tubes 1st and 2nd effects and vapor domes	Corrosion resistance, cleanliness, heat transfer	304	Black liquor	Excellent
Black liquor fuel injector, pumps on recovery boiler	Corrosion resistance	24 Ni, 20 Cr, 3 Mo	Heavy black liquor and salt cake	Excellent
Venturi scrubber recirculation pumps on recovery boiler	Corrosion resistance	24 Ni, 20 Cr, 3 Mo	Heavy black liquor	Excellent
Induced draft fan rotors and casing	Corrosion resistance	304	Gases from furnace	Excellent
Green liquor dissolving tank and agitation equipment	Corrosion resistance	304	Green liquor from causticizing room and smelt from furnace	Good
Green liquor pumps and piping	Corrosion resistance	24 Ni, 20 Cr, 3 Mo and 304	Green liquor	Fair
Causticizing tank and agitation	Corrosion and erosion resistance	304	Green liquor and lime	Good
Green liquor settling tank	Corrosion resistance	304	Green liquor and lime mud	Good
		Screen Room		
All piping	Cleanliness, corrosion resistance	304	Washed stock and water	Excellent
Flow boxes	Cleanliness, corrosion resistance	304	Washed stock and water	Excellent
Head boxes	Cleanliness, corrosion resistance	304	Washed stock and water	Excellent
Screen plates	Cleanliness, corrosion resistance	304	Washed stock and water	Excellent
		Wet Machine Room		
Stock piping	Cleanliness	302	Washed and screened kraft pulp	Excellent
Flow boxes	Cleanliness	302	Washed and screened kraft pulp	Excellent

Table XVII. Experience with Stainless Steels in the Papermaking Cycle

Application	Reasons for Selection	Alloy Type	Environment	Serviceability
Beating Operation				
Stock piping	Cleanliness	302 and 304	Pulp	Excellent
Alum tanks, pipelines, valves, pumps	Corrosion resistance	67 Ni-29 Cu; 82 Fe-14 Si	Alum	Excellent
Beater vats	Cleanliness, corrosion resistance, low maintenance, flexibility	304	Pulp, colors, clays, fillers, sizing, alum	Excellent
Beater measuring tanks	Cleanliness, low maintenance,	304	Sizing	Excellent
Paper Machine				
Stock piping	Cleanliness, flexibility, low maintenance	304	Pulp, slurries for papermaking	Excellent
Flow boxes, mixing boxes, head boxes, couplings, consistency regulators, shake springs and other parts at wet end	Cleanliness, flexibility, low maintenance, corrosion resistance	304	Water, white water and pulp slurry	Excellent
Save-all pans, application pans at presses	Cleanliness, flexibility, maintenance, corrosion resistance	304	Sizing, wet strength, resins, various chemicals	Excellent
Chemical tanks, proportional pumps, valves and piping	Cleanliness, flexibility, maintenance, corrosion resistance	304	Various chemicals for papermaking	Excellent
Exhaust ventilation	Low maintenance, corrosion resistance	304	Moist hot air	Excellent

Types 316 and 347 were cracked in test bombs at 350 to 360 F in 24 hr by a synthetic solution that contained the following:

NaOH	98.8 g
$Na_2S \cdot 9H_2O$	124
$Na_2SO_4 \cdot 10H_2O$	8.6
Na_2CO_3	44.5
H_2O	1000 ml

The sodium hydroxide that contained no chloride and was used alone cracked types 316 and 347; the sodium sulfide that contained less than 50 ppm chloride also caused cracking. Therefore, the presence of chloride may not be essential to cracking.

Perforated backing plates of type 316 stainless steel for paper-pulp washer screens, approximately 0.2 in. thick with cold punched 5/16-in. holes on ½-in. centers, were checked for susceptibility to cracking by immersion in boiling 42% magnesium chloride. Cracking occurred in 18 hr (Fig. 3). Although this test is severe, the known cracking tendencies of pulp-mill washing and bleaching solutions, nearly all of which contain chloride ions, indicate the value of the test. No cracks were evident in the stress relieved equipment after one year of service.

Uses in the Food Industry

Stainless steels are used for their corrosion resistance wherever metal comes in contact with the food product during processing, and because they can be cleaned quickly and easily. Applications include pumps, tubing, tanks, kettles, filling machines, heat exchangers and vacuum tanks. Process temperatures may be as high as 300 F, and the processing may be in vessels operating under pressure or vacuum.

Stainless steels are used also where equipment is subjected to water spray, a continual flow of water, or severe clean-up procedures. In such applications the product does not come in contact with the metal, but the use of carbon steel may cause rust to appear on the surface of the product container or replacement of seriously corroded equipment may be costly. Equipment in this group includes bottle washers, continuous coolers, continuous cookers and conveyers for containers.

In the primary stages of processing, some of the concentrated ingredient solutions are highly corrosive. Pickle liquors and sauces are corrosive, as are other solutions that contain salt and vinegar. Food products such as vegetables contain little acid, and their effect on stainless steels is negligible.

Use of Equipment. The handling of sauces or pickle liquors has caused much difficulty because of pitting of tubing (type 304) at the level of the liquid. Although type 316 is more resistant, tubing of this alloy has been pitted in 4 to 12 months.

Pumps of type CF-8 are used for the less corrosive solutions, such as vegetables; for sauces, pickle liquors and items containing vinegar, type CF-8M is necessary. Because pumps and impellers may need to be interchanged between different processes, type CF-8M is preferred for such units. Type 304 is used for exhaust hoods over open kettles and tanks because of its ability to withstand corrosive fumes and vapors from sauces and liquors containing vinegar. Impellers for the handling of fumes from these tanks and kettles are of type 316. Type 304 is also used for agitators in corrosive solutions and is recommended for tanks to store all products except pickle liquors and sauces; tanks for these should be of 316L, or 316 that has been heat treated, sand blasted, and passivated.

Jacketed kettles and tanks employed for pickle liquors and sauces should be of 316L or 316 that has been heat treated, sand blasted and passivated. Unless 316L or 316 (heat treated) is used, localized pitting will occur at the welded area—often after only 3 months of operation.

Table XVIII. Corrosion by Organic Compounds

Compound and % Concentration	Steel	Temperature, deg Fahr	Corrosion, mpy
40 Chloracetic acid	316	104	5
25 Dichloracetic acid	304	75	<1
100 Ethylene dibromide	304	Boiling	29
25 Glycolic acid	304	150	0.01
95 Glycolic acid	304	150	0.01
Methylene bromide (wet)	304	Boiling	1
99 Propionic acid	316	260	5

Drums to hold dry ingredients such as vegetables are usually of type 304. Tanks used as filler bowls should be made of extra-low-carbon stainless steels to prevent pitting attack adjacent to the welded area. If the filler bowls handle food products less corrosive than sauces, type 304 is recommended.

The equipment must be designed so that the surfaces are kept clean by the product as it is continually flushed across the surface; there must be no crevices or corners where the product could lodge. Welds in corners should be avoided because, in such locations, they cannot be ground smooth.

Many corrosion difficulties can be avoided by frequent cleaning of the stainless steel equipment. At the conclusion of an operation, the equipment is flushed thoroughly with fresh water, then scrubbed with a nylon brush, using a detergent and hot water. After this, the vessel is washed with hot water and rinsed with cold water.

In equipment for the more corrosive food products, the extra-low-carbon stainless steels should be used wherever practicable. Generally, it costs less to use these than to use the regular stainless steels that require heat treatment.

Experience has indicated that a 2B finish (bright, cold rolled) is superior to a No. 4 finish (ground or polished with 120 to 150-grit abrasive). The 2B finish has fewer grooves where food particles could cling.

Test specimens should be suspended beneath the liquid, partly in the liquid, and immediately above the liquid. Welded specimens should be included in the tests. Although laboratory tests are important, the results will not always correlate with actual experience. Data indicating corrosion resistance of stainless steels to food process solutions may be obtained by using the following test solutions.

Solution A

Acetic acid	2.1 %
Salt	6.25
Garlic	0.33

Solution B

Salt Solution	7.5 %

Solution C

Salt solution	2.0 %
Acetic acid	3.0
Sugar	22.0

All three are used at 140 F. Duration of testing varies from a few days to several months.

The Selection of Aluminum Alloy Castings

By the ASM Committee on Aluminum Alloy Castings

THE PURPOSE of this article is to help engineers and metallurgists in the selection of casting method and alloy for parts to be made as aluminum alloy castings. Design data and process limitations are dealt with. Typical variations in mechanical properties are given, supplementing the nominal values published in the 1948 Metals Handbook. Parts are referred to in illustrating factors important in selection.

As shown in Table I, the nominal mechanical properties of many of the aluminum casting alloys are similar. Non-heat-treatable alloys or heat treatable alloys in the annealed condition have a tensile strength of about 15,000 to 20,000 psi, while most alloys in the T6 (heat treated and aged) condition have a tensile strength of 30,000 to 40,000 psi. In a majority of commercial applications any of several alloys might be selected to meet mechanical requirements. Hence, alloy selection must be based on other considerations. Of these, the most important is the cost of the completely finished part.

The cost of the finished part is a function of: (1) the alloy chosen and the inherent technical problems of casting that alloy, (2) the quantity of parts to be procured, (3) the casting process specified, (4) the complexity of the geometric shape of the part, (5) the dimensional tolerances required, (6) the relationship between the as-cast and the finished machined dimensions, tolerances and surface finish, and (7) familiarity of the foundry in casting the alloy selected by the process specified.

Alloy Usage. Although all of the alloys listed in Table I are commercially castable by the processes indicated, the casting industry has established a preference for several alloys for each casting process. Other alloys are less popular because they are not so easy to handle in the foundry. This popularity of certain alloys is made evident by the figures for consumption of secondary alloy in the most widely used processes.

In sand castings, alloys 108 and A108 together represent 37% by weight of all castings produced, followed by alloys of the 7% Cu, 2% Si, 2% Zn type with 36%, alloy 356 with 14%, and a total of 13% for all others. Among permanent mold alloys, D132 represents 41%, followed by alloy 319 with 34%, alloy 43 with 10%, and others 15%.

Subdivisions

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ASM-SLA Al

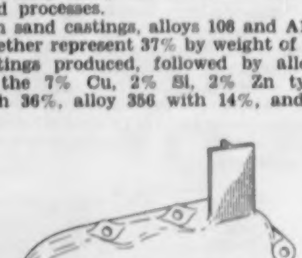

Fig. 1. Cover for Aircraft Engine Rocker Box Made as a Die Casting of Alloy 360 Solely on the Basis of Minimum Cost of Part

In die castings, alloy 380 represents 80%, followed by alloy 13 with 15%, and all others 5%. Many die castings are made of secondary metal because the sodium content of primary metal may cause castings to stick in the die. Also, remelt metal is sometimes considered to be more thoroughly mixed and to have the alloying elements more uniformly dispersed.

A typical example that indicates the selection of a less popular alloy for specific reasons, is shown in Fig. 1, an aircraft engine rocker box cover (approximately 7 in. in largest dimension), which functions as a cover for a working mechanism and prevents loss and contamination of lubricants. Die casting was selected for its economy of large-volume production and alloy 360 for its suitability to die casting as well as its good corrosion resistance. However, should production quantities become considerably smaller—as in phasing a particular part into or out of production—another casting method and alloy might be used.

The casting shown in Fig. 2 is used in an internal assembly where surface finish, porosity and casting tolerances are relatively unimportant. This part is an alignment spacer, and since it is lightly loaded, strength is not an important factor. The choice of sand cast A108 alloy, using an eight-cavity match-plate pattern, was based on the equipment available. The part could be tooled equally well for permanent mold or die casting and, with these methods also, A108 would have been used because it was the standard alloy cast in the foundry chosen and could be produced with few rejects.

Lowest rejection rates of raw castings generally will be experienced when an alloy of high fluidity is specified. Silicon aids fluidity and the popular alloys are high-silicon alloys. Fluidity becomes a more critical factor as the complexity of the part increases or as section size decreases. However, in alloy selection it must be remembered that even though a part lends itself to casting in one of the less fluid alloys, the use of one of the more castable alloys is likely to result in an even lower over-all rejection rate of raw castings at the foundry.

The specification of a heat treatable alloy usually increases the cost of the end product considerably. Therefore, such a choice must be justified on the basis of technical requirements.

Quantity of Parts

The quantity of parts ordered affects the unit cost of the finished part primarily through foundry savings associated with knowledge of how to produce the specific part. If quantities are large enough, die costs for die or semipermanent mold castings may be justified. Figures 3 and 4 show two parts where such studies have been made.

Figure 3 is a comparison of final part costs of centrifugal permanent mold and die castings for an adapter plate, with the permanent mold process showing a cost advantage over the die-casting process for all quantities.

The centrifugal casting process was selected for this part in preference to the standard gravity method because of lower production costs. In spite of the greater die costs associated with the centrifugal process, the higher yield, thinner sections and other factors provide a cost advantage over the gravity method.

Figure 4 gives the final part costs for transmission extension castings produced by permanent mold and die casting methods. The permanent mold method was chosen for this part (produced in quantities of about 3600 castings per day) because of its cost advantage which, seemingly small as depicted on the graph, accumulates significantly over a period of months.

This method of comparing processing costs is as readily adaptable and as valid for short runs as for long. The break-even point between shell molding and investment casting, for example, may occur at less than 100 parts.

Casting Process Specified. The principal types of casting processes are: sand, permanent mold, investment and die.

As is well known, a sand casting can

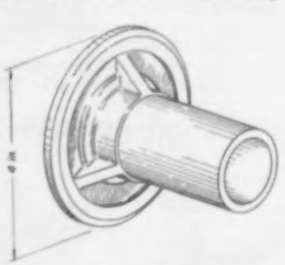

Fig. 2. Alignment Spacer Made of A108 Solely on the Basis of Minimum Cost of the Finished Part

be made using any simple pattern. Gates, risers and sprues can be cut into the sand mold by the molder. Sand casting can be used where minimum investment in tools is dictated by the quantity to be produced. On the other hand, a shell mold casting, which is a high-production sand casting or a semiprecision investment casting (depending on the reader's point of view) requires more elaborate tools. This will raise the price of raw castings for small quantities and probably will reduce it for large quantities.

Permanent mold, investment, and die casting processes all require moderate to large investment in tools. These processes are generally specified where the quantities to be produced or the casting peculiarities justify such larger investments.

Complexity of the geometric shape adds to the cost of every step in the production of a casting—from preparation of the drawing for the part to inspection of the finished article.

Dimensional Tolerances

The relation of tolerances to production costs in casting processes is similar to that in other manufacturing methods. Maximum economy is obtained by allowing as large a tolerance on each dimension as is practicable.

The increase in cost resulting from tighter tolerances holds for all casting methods. The reason is illustrated for investment castings in Fig. 5 and 6. The normal variation in tolerance from pattern dimensions (Fig. 5) and the rate of rejection as related to tolerance on one dimension (Fig. 6) are indicative of the latitude in tolerance that is needed for economical production—even for a method that is usually regarded as highly accurate.

The dimensional tolerances imposed by design requirements may determine what casting method is used. The tolerances across the parting line, between points on one part of the mold, and between points produced by core and mold (illustrated in Fig. 7) are listed for the different casting processes in Table II. These are representative values for normal production practice. It is evident from these figures that the large-volume processes such as sand and permanent mold casting are most suitable for parts on which relatively large dimensional tolerances are acceptable. Investment and plaster mold processes represent the other extreme.

If the parting line tolerance for plaster mold casting is reduced to plus and minus 0.010 in. plus 0.001 in. per in. of length (from the customary 0.0015 in. per in. of length) for 12-in. castings, the increase in casting cost would be about 15%. Similarly, tightening the parting line tolerance by 0.0004 in. per in. of length for shell molding increases the cost by about 15%. Figure 8 gives graphic representation of the spread between minimum and recommended tolerances for centrifugal permanent mold casting. The tolerances given in Fig. 8 are for one side of the parting line and should be increased 50% if the web is on both sides of the parting line. Webs defined on one side by a movable core should have a tolerance of plus and minus 0.010 in. min.

As-Cast and Finished Machined Dimensions. There is some misconception regarding accuracy obtainable with investment castings. Tolerances are closer than on sand castings, for example, and there is a marked reduction in the amount of machining needed for parts made by this process. However, it is still impossible to cast parts to the equivalent of machined dimensions. On a casting with about 30 dimensions and a normal tolerance of about plus and minus 0.010 in. on each dimension, probably 20 to 25 of the tolerances are usually met; the remainder are outside the specified limits.

By casting a part to close tolerances, complex and costly machining operations can often be eliminated. Therefore, direct comparison of cost between an investment casting (or a precision sand casting) and a conventional casting is misleading unless the cost of machining is also considered in the evaluation. It is for this reason that investment casting is most frequently applied to the ferrous metals having low machinability.

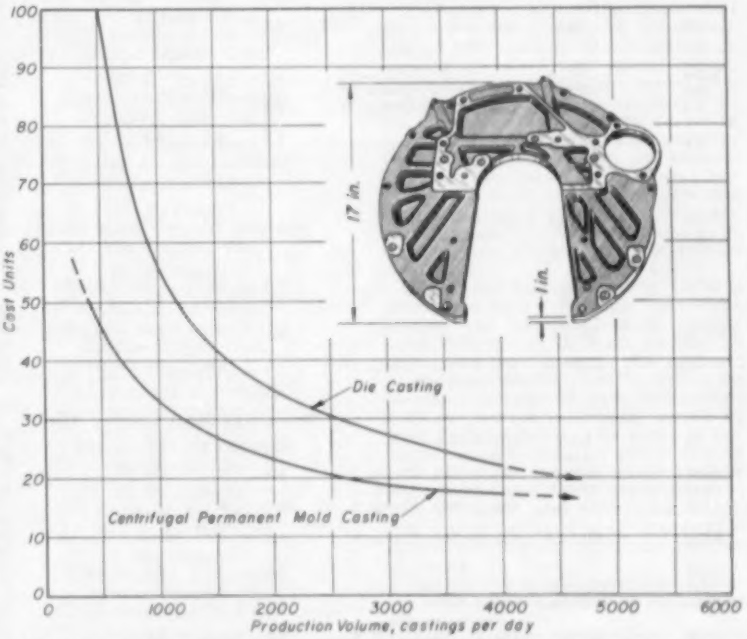

Fig. 3. Cost Comparison for an Adapter Plate as Made by Die Casting and by Centrifugal Permanent Mold Casting

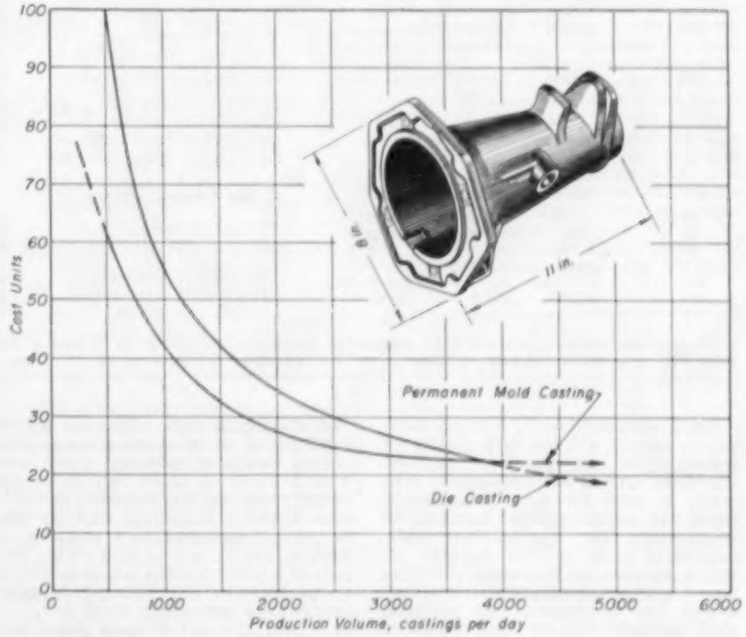

Fig. 4. Cost Comparison for a Transmission Extension Casting Showing Break-Even Point for Two Competitive Casting Processes

Table I. Compositions and Tensile Properties of Aluminum Casting Alloys

Trade Name	ASTM Designation	Government Specification	Nominal Composition, %				Condition[a]	Strength, 1000 psi				Elongation in 2 In., %	
								Tensile		Yield			
			Cu	Mg	Si	Others		Nom	Min	Nom	Min	Nom	Min
Sand Casting Alloys													
43	S5A	QQ-A-601a	...	...	5.0	...	F	19	17	8	6	8.0	3.0
	S5B	Comp 2	...	...	5.0	...	F	..	17	..	7	8.0	3.0
108	CS43A	QQ-A-601a, Comp 8...	4.0	...	3.0	...	F	21	19	14	12	2.5	1.5
113	CS72A	QQ-A-601a, Comp 9...	7.0	...	2.0	1.7 Zn	F	24	19	15	12	1.5	1.0
122	CG100A	QQ-A-601a Comp 7	10.0	0.2	...	...	T2	27	23	20	..	1.0	(b)
							T61	41	30	40	..	(c)	(b)
142	CN42A	QQ-A-601a Comp 6	4.0	1.5	...	2.0 Ni	T21	27	23	..	..	1.0	(b)
							T61	41	32	40	20	..	(b)
195	C4A	QQ-A-601a Comp 4	4.5	...	...	...	T4	32	29	16	13	8.5	6.0
							T6	36	32	24	20	5.0	3.0
							T62	40	36	34	28	1.5	(b)
B214	GS42A	...	...	3.8	1.8	...	F	20	17	13	10	2.0	(b)
220	G10A	QQ-A-601a, Comp 16..	...	10.0	...	...	T4	46	42	25	22	14.0	12.0
319	SC64C	QQ-A-601a, Comp 18..	3.5	...	6.0	...	F	27	23	18	14	2.0	(b)
							T6	36	31	24	20	2.0	1.5
355	SC51A	QQ-A-601a Comp 10	1.3	0.5	5.0	...	T51	28	25	23	18	1.5	(b)
							T6	35	32	25	20	3.0	2.0
							T61	39	36	35	..	1.0	(b)
							T7	38	35	36	..	0.5	(b)
							T71	35	30	29	22	1.5	(b)
356	SG70A	QQ-A-601a Comp 3	...	0.3	7.0	...	T51	25	23	20	16	2.0	(b)
							T6	33	30	24	20	3.5	3.0
							T7	34	31	30	..	2.0	(b)
							T71	28	25	21	..	3.5	3.0
A612	......	...	0.5	0.7	...	6.5 Zn	F	35	32	25	20	5.0	2.0
Allcast	SC8	...	3.0	...	5.0	...	F	27	..	14	..	2.5	...
							T6	35	..	20	..	4.0	...
Red X8	SC82A	...	1.5	0.3	8.0	0.3 Mn	F	..	25	..	14	...	1.0
							T6	39	34	30	21	1.5	1.0
40E	ZG61A	QQ-A-601a, Comp 17..	...	0.6	5.5 Zn	0.5 Cr	T5	..	32	25	22	...	3.0
		MIL-A-17129				0.2 Ti	...	..	..	..	..	...	...
Permanent Mold Casting Alloys													
43	S5A	QQ-A-596a	...	...	5.0	...	F	23	21	9	6	10.0	2.5
	S5B	Comp 7	...	...	5.0	...	F	..	21	..	7	10.0	2.0
A108	SC64A	QQ-A-596a, Comp 5...	4.5	...	5.5	...	F	28	23	16	12	2.0	(b)
C113	CS72A	QQ-A-596a, Comp 1...	7.0	...	3.5	...	F	30	25	24	14	1.0	(b)
122	CG100A	QQ-A-596a, Comp 2...	10.0	0.2	...	...	T551	37	30	35	..	(c)	(b)
							T65	48	40	36	..	(c)	(b)
A132	SN122A	QQ-A-596a, Comp 9...	0.8	1.2	12.0	2.5 Ni	T551	36	31	28	..	0.5	(b)
							T65	47	40	43	..	0.5	(b)
D132	......	...	3.5	0.8	9.0	0.8 Ni	T5	36	31	28	..	1.0	(b)
138	CS104A	...	10.0	0.3	4.0	...	F	30	26	24	..	1.5	(b)
142	CN42A	QQ-A-596a Comp 3	4.0	1.5	...	2.0 Ni	T571	40	34	34	..	1.0	(b)
							T61	47	40	42	..	0.5	(b)
B195	CS42A	QQ-A-596a, Comp 4...	4.5	...	2.5	...	T4	37	33	19	15	9.0	4.0
							T6	40	35	26	22	5.0	2.0
							T7	39	33	20	16	4.5	3.0
A214	GZ42A[d]	...	...	3.8	...	1.8 Zn	F	27	22	16	12	7.0	2.5
B214	GS42A	...	...	3.8	1.8	...	F	22	19	13	..	2.0	1.5
319	SC64C	QQ-A-596a, Comp 11..	3.5	...	6.0	...	F	27	26	19	15	2.0	(b)
355	SC51A	QQ-A-596a Comp 6	1.3	0.5	5.0	...	T51	30	27	24	..	2.0	(b)
							T6	43	37	27	23	4.0	1.5
							T71	36	34	31	27	3.0	...
356	SG70A	QQ-A-596a Comp 8	...	0.3	7.0	...	T6	40	33	27	22	5.0	3.0
							T7	33	29	24	..	5.0	4.0
750	......	...	1.0	...	6.5 Sn	1.0 Ni	T5	20	18	8.5	..	10.0	8.0
Allcast	SC8	...	3.0	...	5.0	...	F	35	..	18	..	3.0	...
Red X8	B108-54T	MIL-A-958 (Ships)	1.5	0.3	8.0	0.3 Mn	...	..	..	..	..	...	...
Red X13	......	...	1.5	0.7	12.0	0.7 Mn	...	..	..	..	..	...	...
Die Casting Alloys													
13	S12A	QQ-A-591a, Comp 1...	...	...	12.0	...	F	39	..	21	..	2.0	(b)
43	S5C	QQ-A-591a, Comp 3...	...	...	5.0	...	F	30	..	16	..	9.0	(b)
85	SC54A	QQ-A-591a, Comp 5...	4.0	...	5.0	...	F	40	..	24	..	3.0	(b)
218	G8A	QQ-A-591a, Comp 7...	...	8.0	...	...	F	45	..	27	..	8.0	(b)
360	SG100A	QQ-A-591a, Comp 12..	...	0.5	9.5	...	F	41	..	23	..	5.0	(b)
380	SC84A	QQ-A-591a, Comp 11..	3.5	..	8.5	..	F	43	..	26	..	2.0	(b)
384	......	...	3.8	...	12.0	...	F	46	..	27	..	1.0	(b)

(a) Solution and precipitation heat treatments, designated by the letter T and a numeral, are defined in 1948 Metals Handbook, page 837; F indicates as-cast condition. (b) Not required for acceptance. (c) Less than 0.5%. (d) B179-49T

Costs associated with foundry techniques usually will not vary greatly for conventional and precision methods. The same type of basic equipment generally is used for both. Occasionally cores will require special handling or preparation that will increase costs. Inspection costs will be directly affected because of the more extensive layout and closer quality standards required for investment and precision sand castings.

The tolerances for shell mold castings depend on the pattern. A pressure-cast aluminum plate will come within 0.030 in. of drawing dimensions. Machined cast iron patterns, which cost 2 to 3 times as much, will serve for longer runs, and the variation in tolerance between individual castings will be reduced considerably. A variation of 0.001 in. per in. can be held within one part of a mold; for the tolerance across the parting line, the parting-line variation of plus and minus 0.015 in. must be added. The cost of these closer tolerances is a pattern cost and not an added cost of foundry operation.

Table III summarizes the available information on dimensional limits and tolerances for the different aluminum casting processes. Several typical examples illustrative of process selection on the basis of dimensional tolerances are described in the section devoted to design considerations (page 56).

While the selection of permanent mold casting for automotive engine pistons (Fig. 9) involves factors of cost and quality as well as dimensional accuracy, this item is indicative of the dimensional accuracy that can be ob-

Table II. Dimensional Tolerances

Casting Process	Tolerance for Dimensional Limits, in. Under 1 In.	Over 1 In., Add per In.
Across Parting Line		
Sand	±0.015	....
Die	....	....
Permanent mold	±0.015	+0.002
Plaster mold	±0.010	+0.0015
Shell mold	±0.010	+0.0012
Centrifugal(a)	±0.010(b) (d)	+0.001(c) (e)
Investment	....	....
Between Points for One Part of Mold		
Sand	±0.015	....
Die	....	....
Permanent mold	±0.015	+0.001
Plaster mold	±0.005	+0.0015
Shell mold	±0.005	+0.0012
Centrifugal(a)	±0.010(b) (f)	+0.001(c) (g)
Investment	....	....
Between Points Produced by Core and Mold		
Sand	±0.015	....
Die	....	....
Permanent mold	±0.015	+0.002
Plaster mold	±0.010	+0.0015
Shell mold	±0.010	+0.0015
Centrifugal(a)	±0.015(b) (h)	+0.001(c) (i)
Investment	....	....

(a) Using permanent molds. (b) For dimensions under 2 in. (c) For dimensions over 2 in. (d) ±0.005 in. min. (e) +0.010 in. per in. min. (f) ±0.005 in. min. (g) +0.010 in. per in. min. (h) ±0.010 in. min. (i) ±0.015 in. per in. min

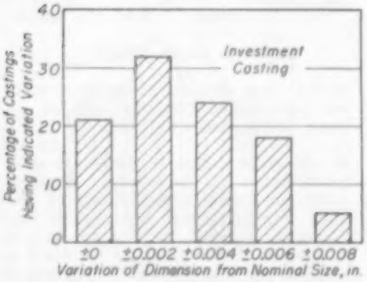

Fig. 5. Distribution in Variation of Dimension of Casting from Dimension of Pattern

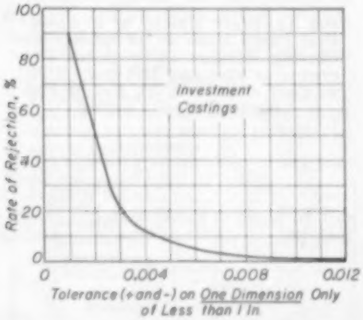

Fig. 6. Effect of Tolerance for One Dimension on Rate of Rejection for Investment Castings

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This article supplements the data on Aluminum Casting Alloys, pages 824 to 840 in the 1948 ASM Metals Handbook.

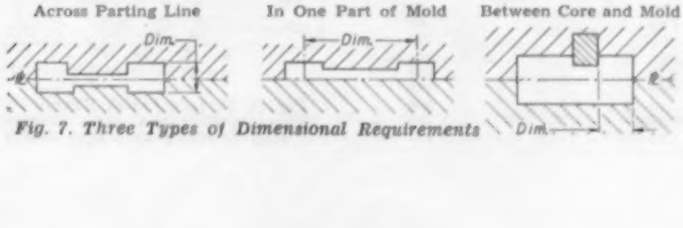

Fig. 7. Three Types of Dimensional Requirements

tained with high-volume permanent mold practice as compared with regular sand casting. The finished weight requirement of plus and minus 2 grams (total weight is 460 g) is obtained by machining more or less metal from two integrally cast boss sections of about 30 g total weight, which are furnished for balancing by a variable depth of cut in final machining. This weight requirement imposes the necessity for much closer casting dimensions (± 0.007 in. on a 3-in. cored section) than are obtainable with regular sand castings.

If in addition to meeting dimensional accuracy and low unit cost, the casting process also must provide intricate or complex die work and precise coring, then die casting would be selected. The transmission control valve shown in Fig. 10 is an example of the degree of complexity and dimensional accuracy that can be produced by die casting. The close dimensional control, very low permissible draft, interlocking cores and general intricacy of this part preclude the use of permanent mold casting, or of any other process for large-volume production.

The reheat fuel pump (Fig. 11) is a production part for which investment casting was selected because dimensional tolerances could not be met by permanent mold casting. The passages of the inner casing must be within an as-cast tolerance of plus and minus 0.003 in. because machining cannot be done in these areas. The areas of opposite passages must be within 10% of each other, the impeller vanes must be smooth and the blade angle must be held to within plus and minus 2 deg. The only machining is on the outside diameter of the casting, for the purpose of fitting.

The surface finish of an as-cast casting is directly dependent on the casting process used.

Usual methods of specifying surface finish as micro-inch roughness are unsatisfactory for cast surfaces, since they measure deviation of tool marks from a smooth condition on a machined surface. A tentative specification for a cast surface comparator has been published recently by a technical committee of the Aircraft Industries Association. This comparator provides visual and touch comparison between production castings and the standard surfaces of the comparator (see Fig. 4 in the article on surface finish, page 83). The approximate micro-inch equivalents for the "C-number" designations of roughness are shown in Table IV.

Figure 12 depicts graphically the range of surface roughness on parts

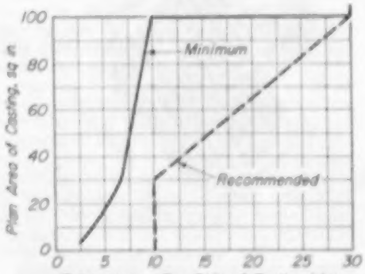

Fig. 8. Minimum and Recommended Tolerances for Centrifugal Permanent Mold Castings

Table III. Dimensional Limits and Tolerances for Aluminum Castings Produced by Different Processes

Sand Castings

Diameter of Cored Holes: Tolerance ±0.030 in. If cored hole is to be used for clearance and a tolerance of ±0.030 in. is necessary, hole should be ordered undersize and machined to tolerance.

Location of Cored Holes: ±0.060 in. approximate minimum for large volume acceptance (±0.015 in. for precision sand castings); can be obtained either by direct tolerance or by reducing hole size correspondingly. If more than one diameter is located from a common centerline, a concentricity tolerance for all diameters can be maintained within ±0.030 in. (±0.015 in. for precision sand method), except as noted under diameter of cored holes. A tolerance of ±0.010 in. (commonly specified) cannot be met consistently.

Straightness: ±0.030 in. per in. of length. Min ±0.005 for precision sand castings.

Allowance for Machining: 0.070 in.; on long, thin castings allowance should be increased to 0.125 in.

Parallelism: Same as under Straightness

Permanent Mold Castings

Maximum Length of Core Supported at One End: 10 × diam of core

Draft on Outer Surfaces: 1 deg min, 3 deg preferred

Draft in Recesses: 2 deg min, 5 deg preferred

Draft on Cores: ½ deg min, 2 deg preferred

Diameter of Core: ¼ in. min

Allowance for Machining: 1/32 in. min for castings up to 10 in. long, 3/64 in. desirable; 3/64 in. min for castings over 10 in. long, 1/16 in. desirable; 1/16 in. for surfaces formed by sand cores.

Minimum Radius of Fillet: Average thickness of joining walls

Straightness: 0.010 in. to 6 in., plus 0.0012 in. per in. of length up to 36 in.

Die Castings

Draft on Outside Surface: ½ deg min

Draft in Cored Holes: 0.020 in. per in. of depth for 1/10 to ⅛ in. diam; 0.016 in. per in. of depth for ⅛ to ¼ in. diam; 0.012 in. per in. of depth for ¼ to 1 in. diam; 0.012 in. per in. of depth plus 0.002 in. per in. of diam for diameters over 1 in.

Plaster Mold Castings

Maximum Length of Core Supported at One End: 5 × diam of core

Draft on Cores: Zero draft often permissible, ½ deg min, otherwise, with 2 deg preferred

Diameter of Core: ¼ in. min

Minimum Radius of Fillet: Sharp corners can be cast

Flatness: 0.0015 in. per in. of length

Shell Mold Castings

Draft on Outside Surfaces: ½ deg min, 2 deg preferred

Straightness: 0.002 in. per in. of length

Investment Castings

Maximum Length of Core Supported at One End: 5 × diam of core (on some parts 10 × diam)

Location of Cored Hole: 0.004 in. per in. of dimension

Concentricity: 0.002 in. per in.

Straightness: 0.005 in. per in. of length

Centrifugal Permanent Mold Castings

Diameter of Core: ⅛ in. min

Draft on Core: ½ deg min for 1 × diam of core, 1½ deg preferred; 1 deg min for 2 × diam, 2 deg preferred; 1½ deg for > 2 × diam, 3 deg preferred

Contour Surfaces: 0.005 in. min for surfaces up to 2 in. long, 0.010 in. preferred; 0.010 in. min for surfaces over 2 in. long; 0.001 in. for each additional inch, 0.030 in. max

Minimum Radius of Fillet: 0.005 in., fillet radius equal to web thickness preferred

Angularity: 0°5′ per in. up to 1 in.; 0°5′ per in. for each additional inch to 30′ max

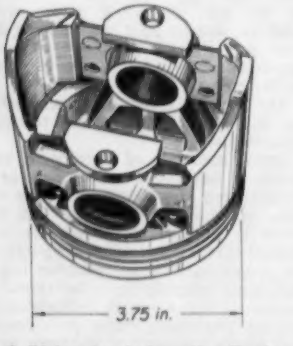

Fig. 9. Piston for Automotive Engine Produced as a Permanent Mold Casting to Casting Dimensions Closer than Can Be Obtained in Sand Casting

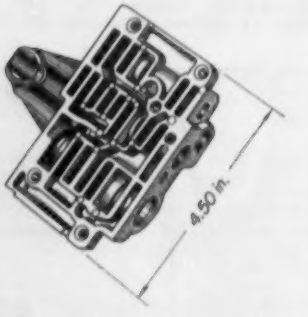

Fig. 10. Transmission Control Valve Body. The close dimensional control, very low permissible draft, interlocking cores and general intricacy virtually preclude the use of any process but die casting for volume production of this part.

produced by each of the casting processes. The surfaces on dies and metal molds eventually deteriorate from contact with the hot metal. This deterioration, commonly called "heat checking", results in the formation of fine cracks into which the metal is forced during casting and, as a consequence, the surface of the casting will have a network of threadlike ridges. Use of dies is limited to about 50,000 castings before redressing; beyond this amount the dies are likely to cause surface imperfections. The valve body shown in Fig. 13 was die cast because the inner surface must be free from the surface roughness normally associated with sand castings, and flat within 0.0005 in. over the shaded area.

Foundry Characteristics

Although similar foundry techniques are used for all aluminum casting alloys, as compared with magnesium, steel and bronze, still each alloy has melting and casting peculiarities of its own. Therefore, a foundry which usually casts alloy 43 will not know all of the detailed variations that must be incorporated into the casting techniques for alloy 220.

Besides these fundamental technical

Table IV. Roughness Designations for Cast Surfaces

C-Number	Approximate Rms Micro-Inch Equivalent
C10	20
C20	60
C30	120
C40	200
C50	300
C60	420
C70	560
C80	720
C90	900

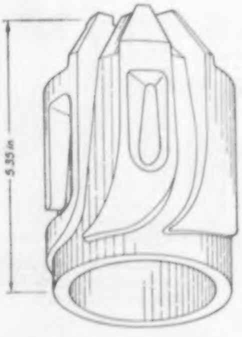

Fig. 11. Inner Casing of a Reheat Fuel Pump Made as an Investment Casting Because Dimensional Tolerance of Plus and Minus 0.003 In., As Cast, Could Not Be Met by Permanent Mold Casting

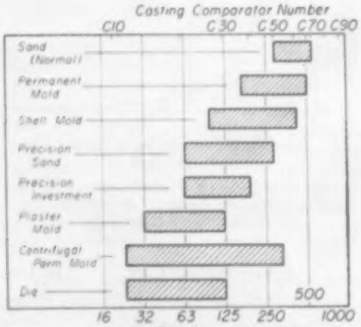

Fig. 12. Surface Finish Ranges Produced by Various Casting Processes and the Micro-Inch Equivalents

difficulties, there are also secondary practical considerations that affect price. These include the necessity for capital investment in spare furnaces to melt "special alloys", large inventories of little used remelt ingots, and housekeeping to prevent contamination during melting, casting and remelting of factory scrap.

Thus despite a sizable difference in prices of the various casting alloys (for example, 1½¢ per lb between alloy 113 and the more expensive A108), these differences generally disappear through differences that exist in processing costs because of individual foundry techniques and standardization with given alloys. It is not unusual for foundries that have standardized their processing for at most two or three alloys to save more by this means than the difference in metal cost. Also, because of design requirements, certain alloys might be more desirable for their strength properties even though the casting properties are inferior, and the knowledge needed to produce sound castings from such alloys could be a valuable asset. However, the quantity of parts to be made, the standards of quality that must be met, and the tolerances required generally have more effect, singly or in combination, on the cost of the part, than does alloy selection. For this reason, the engineer has a range of choice wider than might be generally believed, in regard to alloys suitable for a particular process, without increasing the cost of processing.

Cost Analysis

The relation of various cost factors may be illustrated by considering the cost of an aluminum permanent mold casting.

Three phases of the process are of principal importance in determining costs in the foundry: metal handling, mold design and operation, and handling of the finished castings. Although all three are correlative and present in all types of foundries, it is particularly in the design and operation phases that the permanent mold process can be adjusted to reduce the cost of the cast product.

The three phases can be restated in terms of the following seven factors:

1. Cost of molten metal
2. Labor for mold operation (includes overhead burden)
3. Casting yield at mold
4. Trim and cleanup
5. Special treatments and tests (heat treating, pressure tests for leakage and similar requirements)
6. Miscellaneous (inspection, straightening, packing)
7. Foundry scrap

Cost of Molten Metal depends on the melting practice. Three basic practices are employed in permanent mold foundries: (1) foundry melting of metal purchased under the specified alloy type; (2) foundry alloying of purchased commercially pure aluminum to the specified alloy type; (3) foundry melting of purchased scrap with necessary refining and alloying (also remelting of their own rejected castings and scrapped gates and risers).

The first method, which is the most widely used, is considered here. The relative weight of the items constituting the cost of molten metal in the ladle ready for pouring may be summarized as follows, for this method:

Purchased alloy charge	92.3%
Melting costs	3.1
Melting loss	4.5
Additives	0.1
	100.0

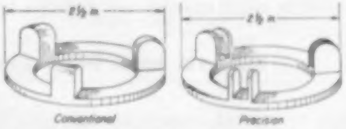

Fig. 14. Part Redesigned from a Conventional Sand Casting to a Precision Sand Casting. Savings in cost of machining more than offset the increased cost of casting.

Table VI. Minimum Section Thickness for Aluminum Castings Produced by Different Processes

Section Thickness, in.	For Length of
Sand Castings	
1/8	Under 3 in.
5/32	3 to 6 in.
3/16	Over 6 in.
Permanent Mold Castings	
0.100	Under 3 in.
0.125	3 to 6 in.
0.160	Over 6 in.
Die Castings	
0.050	Small parts
0.080	Large parts
Plaster Mold Castings	
1/16	3 in. or less
3/32	3 to 6 in.
1/8	Over 6 in.
Shell Mold Castings	
1/16	Under ½ in.
3/32	½ to 3 in.
1/8	3 to 6 in.
5/32	Over 6 in.
Precision Sand Castings	
0.080	Under 3 in.
0.100	3 to 6 in.
0.100	Over 6 in.
Investment Castings	
0.035	¼ in.
0.060	2 in. or less
0.090	2 to 4 in.
0.125	4 to 8 in.
0.150	Over 8 in.

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0.070 in. for up to 4 sq in. per casting, 0.080 for 5 to 10 sq in., 0.090 for 11 to 20, 0.100 for 21 to 30, 0.110 for 31 to 70, 0.120 for 71 to 100, and 0.156 in. for over 100 sq in. per casting. See also Fig. 8.

Table V. Cost Analysis for Two Aluminum Permanent Mold Castings of 319 Alloy from the Same Foundry

Cost Factor	Example 1	Example 2
Total cost of molten metal	86.0%	41.2%
Labor for mold operation	7.7	30.5
Casting yield at mold	2.7	3.2
Trim and cleanup	1.9	16.0
Special operations	0	0
Miscellaneous	1.3	3.4
Foundry scrap	0.4	5.7
	100.0	100.0

Cost of purchased alloy will vary with alloy type, source and market fluctuation. Melting costs, based on the use of a central breakdown furnace and transfer to holding furnaces, includes fuel, labor and maintenance. Melting loss, usually of the order of 5%, covers the loss of metal through oxidation. Irrecoverable scrap is also included in this figure. Additives include flux, grain refiners, or other special treatments that are needed for the particular alloy chosen.

Labor for Mold Operation refers to the mold operator, who may also pour the casting. This term includes, in general, all of the labor—molding, core making and shakeout—needed to convert the molten metal to a rough casting. Good management and the use of automation can keep this cost at a minimum.

Casting Yield at the Mold is the ratio of pounds of salable castings to pounds of metal poured. It is, of course, related closely to part geometry and mold design. However, its effect is so great on the length of the casting cycle and on the amount of trim and cleaning, as well as on the over-all cost of melted metal, that it is included as a separate item in cost analysis. For example, yields have been observed from 30 to 85% in permanent mold foundries, which indicates excessive variation in types of gating design.

Trim and Cleanup costs are important factors in the final cost of castings. Large benefits can result from wise choice of trim dies and automatic cleaning equipment but the greatest saving can be made by reducing trim and cleaning costs through careful selection of gating design.

Special Cost Factors, such as heat treatment, pressure tests and special inspection and test methods, may have important effects. Each of these items may double or triple the cost of raw castings. The engineer must be careful to specify only those controls necessary to produce a usable quality part. These requirements must be limited, particularly in the high-volume field.

Miscellaneous items include routine inspection and preparation for shipment, as well as straightening, which, when required, is often a part of the inspection operation.

Foundry Scrap indicates the over-all

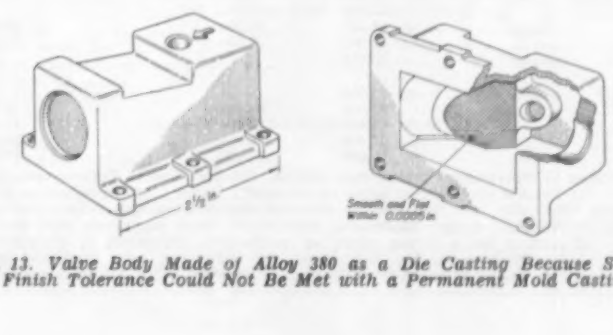


Fig. 13. Valve Body Made of Alloy 380 as a Die Casting Because Surface Finish Tolerance Could Not Be Met with a Permanent Mold Casting

knowledge of the engineer, the consideration given to designing a castable part, and the efficiency of the foundry operation and control. Foundry control should be applied to all operations and it should be a part of supervision overhead and not something applied to a certain job to get out of trouble. Scrap rates in excess of 5% should be scrutinized carefully.

In many instances not enough attention is given to the possibilities for mechanization; manual operation of the mold may result in a requirement of several men per mold or, at best, low production per man-hour. If the same amount of automation utilized in die casting can be applied to permanent molds, considerable economic benefits can be realized.

The effect of these cost factors is summarized in Table V for two production castings of 319 alloy from the same foundry. The choice of alloy type, once the basic price effect is recognized, should not enter as an important economic factor in the permanent mold foundry; every satisfactory design permits utilization of a satisfactory alloy—that is, one that has the necessary foundry requirements. Any other basis admits to error on the part of either consumer design or foundry practice. Quantity is important in most problems of selection and is the basis on which price of the cast part and amortization of the die and tooling investment are determined.

An example of the importance of machining costs is the part made by conventional sand casting shown in Fig. 14. Although the castings cost only 25¢ each, machining cost was $3.75, or a total of $4.00 for the finished part. The part was redesigned for precision sand casting, as shown in the right-hand view in Fig. 14, and even though the casting cost increased to 75¢ each, machining cost was decreased to 30¢, thus reducing the total cost to $1.05—a saving of $2.95 per part. Smaller savings are often obtained by decreasing machining operations as a result of coring and close tolerances in the permanent mold and die casting processes.

Shop Practices

The review of cost considerations shows how difficult and possibly misleading it would be to compile a list indicating the comparative rejection rates that might be expected from the various casting alloys. The reasons for a high rejection rate for a particular alloy in one shop, as compared with that same alloy in another shop, may be problems other than the inherent characteristics of the alloy itself.

Individual shop practices will vary far more than the foundry properties of the various alloys as long as each alloy falls within established chemical specification limits. Poor foundry practice can cause high rejection rates even with alloys that normally give little casting trouble. The quantity of parts to be made, the standards of quality to be met, the tolerances required and probably the foundry casting the parts have more effect on rejections and cost than does alloy selection.

Design Considerations

Knowledge of the casting processes and their limitations is necessary to prevent specifying casting methods and features that exceed the process limitations. For example, the limitations with regard to minimum section thickness might overrule a selection made tentatively on the basis of cost, or conversely it could insure that the part is designed to meet this or other limitations of the process. Also, expensive and perhaps unnecessary details of design can be modified to permit conventional and economical manufacture.

Thin walls (within the limits of strength requirements) are dictated by casting economics. However, the practicable minimum wall thickness is governed by the necessity for filling the mold or die and varies to some degree with the casting process. The general limits for the different casting processes are given in Table VI.

Sections considerably thinner than those listed in Table VI can be produced if the casting is of a shape that permits good flow of metal. Two examples of parts of this kind (and of the processes chosen to produce them) are

Table VII. Static Design Values for Aluminum Casting Alloys

Alloy	Strength, psi Tensile Ultimate (F_{tu})	Tensile Yield (F_{ty})	Compressive Yield (F_{cy})	Shear Ultimate (F_{su})
Sand Casting Alloys				
40E-T5	32,000(a)	20,000(a)	......	27,000(a)
43	17,000(d)	6,000(c)	7,000(c)	11,000(c)
108-F	19,000(d)	12,000(c)	13,000(c)	15,000(c)
108-T55	21,000(d)	......	......	......
113-F	19,000(d)	10,000(c)	11,000(c)	15,000(c)
122-T2	23,000(d)	......	......	......
122-T61	30,000(d)	29,000(c)	31,000(c)	21,000(c)
142-T2	23,000(d)	14,000(c)	14,000(c)	16,000(c)
142-T571	29,000(d)	27,000(c)	30,000(c)	23,000(c)
195-T4	29,000(a)	13,000(a)	14,000(a)	22,000(a)
195-T6	32,000(a)	20,000(a)	21,000(a)	24,000(a)
195-T62	36,000(d)	30,000(c)	32,000(c)	28,000(c)
195-T7	29,000(d)	......	......	......
214-F	22,000(d)	9,000(c)	9,000(c)	15,000(c)
220-T4	42,000(a)	22,000(a)	23,000(a)	30,000(a)
319-F	23,000(d)	14,000(c)	15,000(c)	18,000(c)
319-T6	31,000(d)	19,000(c)	20,000(c)	24,000(c)
355-T51	25,000(d)	20,000(c)	21,000(c)	19,000(c)
355-T6	32,000(d)	20,000(d)	21,000(c)	23,000(c)
355-T7	35,000(d)	33,000(c)	35,000(c)	25,000(c)
355-T71	30,000(d)	24,000(c)	25,000(c)	21,000(c)
356-T4	25,000(d)	......	......	......
356-T51	23,000(d)	18,000(c)	19,000(c)	18,000(c)
356-T6	30,000(a)	20,000(a)	20,000(a)	25,000(a)
Permanent Mold Casting Alloys				
43	21,000(e)	7,000(c)	7,000(c)	13,000(c)
A108-F	24,000(e)	12,000(c)	13,000(c)	18,000(c)
113-F	24,000(e)	15,000(c)	16,000(c)	18,000(c)
122-T551	30,000(e)	28,000(c)	33,000(c)	23,000(c)
122-T65	40,000(e)	28,000(c)	28,000(c)	28,000(c)
A132-T551	31,000(e)	23,000(c)	23,000(c)	23,000(c)
A132-T65	40,000(e)	36,000(c)	36,000(c)	29,000(c)
142-T571	34,000(e)	28,000(c)	28,000(c)	24,000(c)
142-T61	40,000(e)	35,000(c)	37,000(c)	28,000(c)
B195-T4	33,000(a)	20,000(a)	20,000(a)	25,000(a)
B195-T6	35,000(a)	22,000(a)	22,000(a)	26,000(a)
B195-T7	33,000(e)	14,000(c)	14,000(c)	24,000(c)
319-F	29,000(e)	......	......	......
319-T6	40,000(e)	......	......	......
355-T6	37,000(a)	23,000(a)	23,000(a)	26,000(a)
355-T51	27,000(e)	22,000(c)	23,000(c)	21,000(c)
355-T62	42,000(e)	37,000(c)	37,000(c)	33,000(c)
355-T71	34,000(e)	29,000(c)	29,000(c)	25,000(c)
356-T6	33,000(a)	22,000(a)	22,000(a)	25,000(a)
356-T7	29,000(e)	20,000(c)	20,000(c)	21,000(c)
Die Casting Alloys (Typical)[f]				
13	37,000	19,000	......	23,000
13X	35,000	......	......	......
43	30,000	16,000	......	19,000
85	38,000	22,000	......	24,000
85X	35,000	......	......	......
214X	41,000	......	......	......
218	41,000	23,000	......	23,000
360	43,000	26,000	......	27,000
A380	41,000	20,000	......	24,000
380	43,000	24,000	......	27,000

(a) Specified in Government publication ANC-5. (b) Specified in Federal specification QQ-A-591. (c) Typical commercial value minus safety factor. (d) Specified in Federal specification QQ-A-601. (e) Specified in Federal specification QQ-A-596. (f) Typical properties, rather than design minimums, determined from separately cast test bars. Since rate of cooling has a strong effect on mechanical properties of aluminum die castings, actual properties can be determined only with test bars machined from a particular casting. Values obtained from Federal specification QQ-A-591 and other sources.

Table VIII. Average Tensile Properties of Specimens Machined from Aluminum Alloy Castings of Various Thicknesses

Section Thickness, in.	Tensile Strength: Number of Tests	Tensile Strength: Average Value, psi	Tensile Strength: Ratio to Minimum,[a] %	Yield Strength: Number of Tests	Yield Strength: Average Value, psi	Yield Strength: Ratio to Minimum,[a] %	Elongation: Number of Tests	Elongation: Average Value, %	Elongation: Ratio to Minimum,[a] %
Sand Cast Alloy 220-T4									
Up to ¼	437	31,900	76	15	25,100	114	437	6.7	56
¼ to ½	1562	32,400	77	343	25,600	117	1562	6.8	57
9/16 to 1	1496	31,500	75	43	25,100	114	1495	6.4	53
1-1/16 to 2	328	30,500	73	28	24,400	111	336	5.9	49
Specified minimums		42,000	in separately cast specimens		22,000	in separately cast specimens		12.0	
Typical values		46,000	in separately cast specimens		25,000	in separately cast specimens		14.0	
Sand Cast Alloy 356-T6									
Up to ¼	152	30,600	102	134	24,000	120	152	3.3	109
¼ to ½	452	29,100	97	270	23,200	116	452	3.3	109
9/16 to 1	152	32,400	108	123	22,400	112	152	3.0	100
1-1/16 to 2	41	24,900	83	...	...	...	41	1.4	45
Specified minimums		30,000	in separately cast specimens		20,000	in separately cast specimens		3.0	
Typical values		33,000	in separately cast specimens		24,000	in separately cast specimens		3.5	
Permanent Mold Cast Alloy 356-T6									
Up to 3/16	16	33,700	102	16	26,200	119	16	3.5	117
3/16 to ½	107	33,000	100	107	26,000	118	107	4.8	160
9/16 to 1	45	32,700	99	45	27,700	126	45	4.9	163
Specified minimums		33,000	in separately cast specimens		22,000	in separately cast specimens		3.0	
Typical values		40,000	in separately cast specimens		27,000	in separately cast specimens		3.5	

(a) Ratio of average properties for specimens machined from castings to specified minimum properties of separately cast specimens

Table IX. Typical Tensile Properties of Test Bars Cut from Castings

Thickness of Casting, in.	Tensile Strength, psi	Yield Strength, psi	Elongation in 4 Diam, %
Sand Cast Alloy 195-T6			
Under ⅛	37,500	27,500	6.0
⅛ to ¼	37,000	27,000	5.5
¼ to ½	37,000	26,500	4.0
½ to ¾	35,500	25,250	4.0
¾ to 1	32,000	24,500	3.0
Minimum[a]	32,000	20,000	3.0
Nominal	36,000	27,000	5.0
Sand Cast Alloy 355-T6			
Under ⅛	36,500	26,000	4.5
⅛ to ¼	36,000	25,750	4.0
¼ to ½	36,000	25,500	4.0
½ to ¾	35,500	25,000	3.5
¾ to 1	33,000	23,000	3.5
Minimum[b]	32,000	20,000	2.0
Nominal	35,500	25,500	4.0
Sand Cast Alloy 356-T6			
Under ⅛	37,000	25,500	5.0
⅛ to ¼	35,500	24,500	4.5
¼ to ½	34,000	23,500	4.0
½ to ¾	32,500	22,500	3.5
¾ to 1	31,000	21,500	3.0
Minimum[a]	30,000	20,000	3.0
Nominal	33,500	24,300	4.0

(a) Requirements specified in Air Force-Navy-Civil Aeronautics Publication ANC-5
(b) Requirements specified in Federal specification QQ-A-601

Table X. Tensile Properties for Castings of Alloy 356-T6

Thickness of Casting, in.	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 In., %
Tentative Minimum Requirements of ARTC for Castings Made by Any Process[a]			
0 to 0.124	36,000	24,000	5.0
0.125 to 0.249	34,500	23,000	4.5
0.250 to 0.499	33,000	22,000	4.0
0.500 to 0.749	31,500	21,000	3.5
0.750 to 1.000	30,000	20,000	3.0
Typical Values for Permanent Mold Castings[b]			
0 to 0.124	43,000	31,000	6.0
0.125 to 0.249	42,000	30,000	5.0
0.250 to 0.499	40,000	30,000	4.0
0.500 to 0.749	37,000	29,000	2.0
0.750 to 1.000	37,000	28,000	2.0
1.001 to 1.500	36,000	28,000	1.25

(a) Issued by the Aircraft Technical Committee, Aircraft Industries Assoc, in report ARTC-10. (b) Based on tests by user of standard specification alloys for aircraft castings

shown in Fig. 15 and 16. The casting in Fig. 15, produced as a precision sand casting, is a production item having a wall thickness of 0.050 in. This is an extremely thin-walled casting; wall thicknesses of 1/8 to 1/10 in. are more common for castings made by this method. The 2⅛-in. diam plunger guide shown in Fig. 16, made by die casting A380 alloy, also has section thicknesses of 0.050 in. Walls in this thickness range can be produced in die castings that are less than about 6 by 6 in. over all.

In the permanent mold process, minimum section thicknesses of 0.060 to 0.090 in. can be produced in some small castings. The section sizes given in Table VI are more normal. Over-all dimensional limits and tolerances for the various casting processes are given in Tables II and III.

Surface Smoothness of the casting may be necessary but it influences casting efficiency, and the process deserves consideration in this respect. For example, some roughness on the die surface, in die casting, improves metal flow; a polished die surface often is troublesome until it is broken in. Good gating practice for certain areas requires some roughness in the feed gates.

The major factor determining surface roughness on parts cast in sand is the fineness of the molding sand. The range given in Fig. 12 for surface roughness on normal sand castings does not include the available limit of 250 micro-in. and less on fine sand castings. However, such refinement of surface should not be specified unless there is justification for the additional cost.

The smoothest surfaces produced by conventional methods are those made from metal molds. Permanent mold casting employing sand cores, generally termed semipermanent mold casting, and centrifugal casting with sand molds produce surfaces typical of the smoother finishes obtained on a conventional sand casting. The sand used in shell molds is generally finer than for the other sand casting methods. Production parts, shell molded, have a surface finish comparable to 100 to 375 micro-in. (Fig. 12). For instance, an air

Table XI. Comparison of Average Tensile Properties for As-Cast Test Bars and Specimens Machined from Cylindrical Castings of Various Diameters

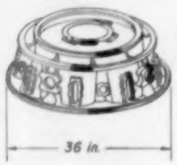
Source of Sample	Tensile Strength, psi	0.2% Yield Strength, psi	Elongation, %
Alloy 355-T6			
As-cast test bar	27,100	...	1.3
Machined from ¾-in. round	27,300	24,600	1.0
Machined from 1¼-in. round	22,000	20,300	1.0
Machined from 1¾-in. round	19,100	18,800	..
Machined from 2¼-in. round	18,100	17,700	1.0
Alloy 355-T51			
As-cast test bar	34,800	23,400	3.3
Machined from ¾-in. round	29,000	23,000	1.7
Machined from 1¼-in. round	26,900	22,200	1.0
Machined from 1¾-in. round	23,200	20,800	1.0
Machined from 2¼-in. round	21,300	20,800	1.0
Alloy 356-T6			
As-cast test bar	34,100	24,300	4.6
Machined from ¾-in. round	28,300	23,000	2.0
Machined from 1¼-in. round	23,000	22,500	1.0
Machined from 1¾-in. round	19,400	...	0.7
Machined from 2¼-in. round	15,100	...	0.5
Alloy 356-T51			
As-cast test bar	27,200	...	1.6
Machined from ¾-in. round	21,900	16,700	1.5
Machined from 1¼-in. round	17,150	13,480	1.3
Machined from 1¾-in. round	14,400	12,700	1.2
Alloy 195-T6			
As-cast test bar	39,800	22,300	6.4
Machined from ¾-in. round	29,100	16,800	5.0
Machined from 1¼-in. round	29,300	19,900	4.3
Machined from 1¾-in. round	22,600	17,200	2.3
Machined from 2¼-in. round	22,100	18,100	2.5
Alloy 195-T51			
As-cast test bar	24,400	...	6.1
Machined from ¾-in. round	20,300	9,300	5.5
Machined from 1¼-in. round	18,200	9,800	3.2
Machined from 1¾-in. round	15,900	10,000	2.3
Machined from 2¼-in. round	13,900	10,500	1.0

Table XII. Tensile Properties of Specimens Cut from Different Parts of a Rear-Frame Jet Engine Casting (Alloy 355-T51)

Specimen Location	Section Thickness, in.	Tensile Strength, psi	Elongation, %
Port flange	½	21,333	2.9
Fuel injector pad	⅛	22,107	1.5
Firewall flange	⅛	19,164	2.8
Air seal pad	¾	19,845	1.6
Trunnion pad	1	19,412	1.6
Stud ring flange	1	19,298	1.8
Forward flange	1	19,658	1.6
Bearing flange	1⅛	18,380	1.6

Specimen Locations on—

Front View of Part



Back View of Part

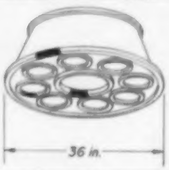
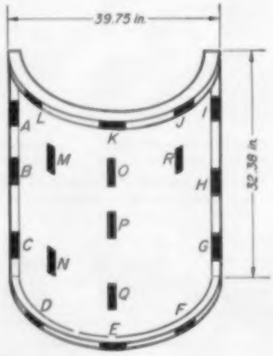


Table XIII. Short-Time Tensile Properties of Specimens Cut from a Jet Engine Compressor Casting (Alloy 355-T71)

Specimen Location	Temperature of Test, deg Fahr	Tensile Strength, psi	Yield Strength (0.2% Offset), psi	Elongation, in 2 In., %
Specimens Tested at 70 F				
B	70	25,200	21,700	1.0
D	70	27,900	23,600	1.5
H	70	24,875	22,400	1.0
K	70	23,350	22,300	1.0
M	70	24,125	22,650	1.0
P	70	23,050	21,450	1.0
Specimens Tested at 450 F				
C	450	15,400	9,000	12.0
F	450	17,150	8,600	13.0
I	450	14,050	9,375	7.0
L	450	13,400	8,750	6.0
N	450	14,625	8,950	7.0
O	450	13,850	8,650	5.5
Specimens Tested at 600 F				
A	600	11,650	6,500	33.0
E	600	11,700	6,900	38.0
G	600	11,450	6,850	35.0
J	600	10,900	6,700	41.0
Q	600	10,800	6,400	46.0
R	600	11,350	6,500	39.0

Specimen Locations



See Fig. 20 for scatter in tensile properties at room temperature for this alloy.

Table XIV. Creep-Rupture Properties of Some Aluminum Casting Alloys

Alloy	Rupture Strength, psi							
	300 F		400 F		500 F		600 F	
	100 hr	1000 hr	100 hr	1000 hr	100 hr	1000 hr	100 hr	1000 hr
355-T6	...	28,000	...	11,200	...	6,700	...	2,300
A355-T6	29,000	25,000	18,000	15,000	10,000	7,000	4,350	2,800
ML-T6	32,000	28,000	22,000	18,000	14,000	12,500	9,400	6,400
142-T6	32,500	30,000	25,000	22,000	16,000	11,500	5,700	2,700
XA140-T2	35,000	30,000	20,000	16,000	11,000	8,000	5,000	3,500
RR 250-T6	22,000	17,500	15,000	12,000	8,800	6,800	4,200	2,600

For standard test bars, separately cast

intake diffuser for which the surface roughness requirements are 200 micro-in. max, is cast consistently with a roughness of 120 micro-in. by the shell molding process.

The surface finish on all investment castings is determined primarily by the surface finish of the pattern tools and patterns. Investment castings usually are substantially less precise or smooth than the expendable patterns (wax and plastic), due to casting imperfections. No amount of subsequent care in foundry practice, except surface finishing, will produce a smoother surface on the castings (as cast) than that initially imparted to the wax or plastic pattern by the pattern dies. However, pits and other surface irregularities arising from cracks, shift, chips or other investment flaws that affect the quality of the surface can be minimized by careful foundry technique. Investment casting was selected for producing the part shown in Fig. 17, in order to meet a requirement of C-30 (approx 125 micro-in.) surface roughness.

Mechanical Properties

The mechanical properties of cast test coupons are widely used as an indication of metal quality. Some data on mechanical properties (particularly yield strength) are nearly always required in design. For these reasons, greater efforts have been involved in the quantitative determination of mechanical properties than in research on any other characteristic of aluminum casting alloys.

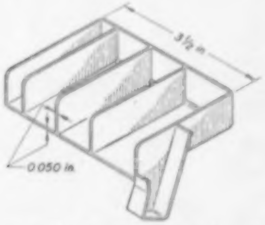


Fig. 15. Production Precision Sand Casting with Wall Thickness of 0.050 In.

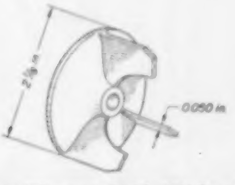


Fig. 16. Plunger Guide Made of 380 for Which Die Casting Was Selected Because Sections Had to Be Thinner than Could Be Cast in a Permanent Mold

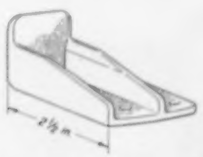
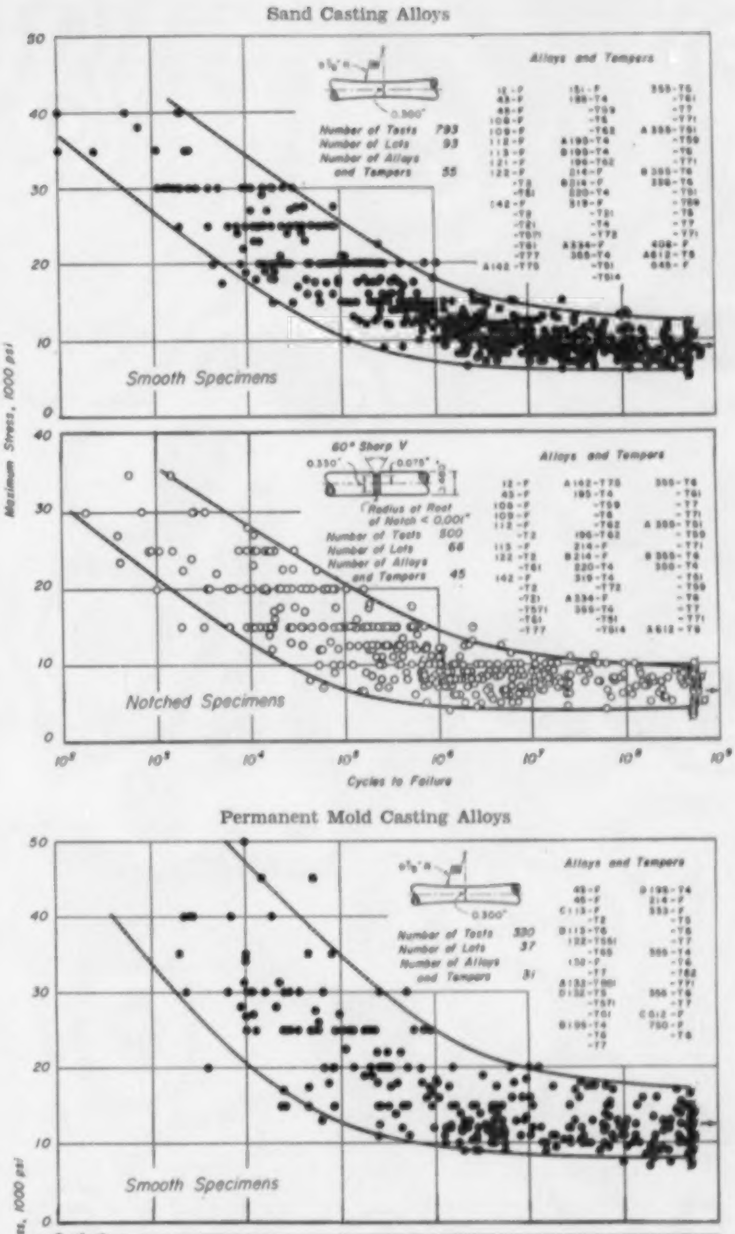


Fig. 17. Investment Cast Part Which Would Not Have Been Satisfactory as a Sand Casting Because of Surface Finish Requirement of C-30


Sand Casting Alloys

Permanent Mold Casting Alloys

Fig. 18. Scatter Bands Showing Range of Fatigue Strengths for Aluminum Sand Casting Alloys (Top of Page) and Permanent Mold Casting Alloys (Bottom)

Table XV. Creep-Rupture Properties

Alloy	Stress to Cause Rupture in 1000 Hr At 300 F, psi	Stress to Cause Rupture in 1000 Hr At 400 F, psi
Sand Castings		
43-F	10,500	6,500
142-T61	......	22,500
195-T6	20,000	11,500
B214-F	20,500	11,500
319-T71	17,000	12,000
319-F	20,000	15,500
355-T51	......	8,500
356-T7	19,500	8,500
Permanent Mold Castings		
D132-T5	27,000	16,500
B195-T6	21,000	12,000
355-T62	29,000	12,000

Representative values; test data are too few to establish the normal range.

Table XVI. Short-Time Tensile Properties of Specimens Cut from a Jet Engine Compressor Casting (Alloy 355-T71)

Temperature of Test, deg Fahr	Tensile Strength, psi	Elongation in 2 In., %	Temperature of Test, deg Fahr	Tensile Strength, psi	Elongation in 2 In., %
Cast Test Bars			**Left Flange, 2-In. Section**		
70	33,600	1.3	70	25,600	0.25
200	31,750	1.5	200	28,390	0.25
450	22,700	3.4	450	21,125	0.75
Top Flange, 2-In. Section			**Right Flange, 2-In. Section**		
70	27,650	0.25	70	26,500	0.25
200	27,800	0.25	200	28,250	0.25
450	21,500	0.75	450	21,970	0.75
Bottom Flange, 2-In. Section			**Body, 1-In. Section**		
70	30,850	1.00	70	28,000	0.25
200	31,400	0.50	200	26,050	0.25
450	24,400	1.75	450	20,500	0.75

Semicylindrical casting of 15-in. radius, 30-in. length and flanged on all four edges

Table XVII. Short-Time Tensile Properties of Some Aluminum Casting Alloys at Elevated Temperature

Specimen Condition(a)	Measured at Room Temperature				Testing Temperature, deg Fahr	Measured at the Elevated Temperature Indicated(a)			
	Modulus, 10^6 psi	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 In., %		Modulus, 10^6 psi	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 In., %
Alloy 355-T51									
As heat treated	9.5	28,795	23,340	1.6	...	...	...	...	...
Aged 100 hr, 300 F	9.49	27,000	23,570	1.8	300	8.2	24,500	19,500	2.0
Aged 100 hr, 400 F	7.93	26,067	21,607	1.8	400	9.36	21,400	17,375	3.2
Aged 100 hr, 500 F	8.72	23,420	12,907	3.3	500	6.40	12,620	9,155	7.0
Aged 100 hr, 600 F	5.35	20,125	10,050	4.2	600	4.5	7,970	5,375	19.3
Alloy 355-T6									
As heat treated	9.64	36,465	33,940	2.0	...	...	...	...	...
Aged 100 hr, 300 F	9.0	40,500	37,500	2.0	300	9.34	41,325	33,630	3.3
Aged 100 hr, 400 F	8.77	41,000	38,775	0.5	400	9.3	32,030	30,165	1.0
Aged 100 hr, 500 F	6.07	24,400	13,500	5.0	500	5.35	13,380	8,330	11.0
Aged 100 hr, 600 F	4.8	23,950	9,175	7.3	600	4.6	7,345	4,930	32.0
Alloy A355-T6									
As heat treated	9.5	38,550	29,900	1.5	...	...	...	...	...
Aged 100 hr, 300 F	10.5	44,600	41,270	0	300	10.3	40,680	38,160	0.8
Aged 100 hr, 400 F	10.5	36,570	32,080	0.7	400	9.1	29,570	24,740	2.0
Aged 100 hr, 500 F	9.8	25,910	13,860	3.0	500	10.3	14,060	10,920	12.0
Aged 100 hr, 600 F	9.8	22,630	11,720	2.7	600	6.3	9,000	6,480	15.5
Alloy ML-142-T6 (4% Cu, 2% Mg, 2% Ni, 0.1% Ti, 0.3% Cr, 0.03% V)									
As heat treated	10.5	41,000	37,600	1.0	...	...	...	...	...
Aged 100 hr, 300 F	10.5	43,250	38,850	0	300	9.9	40,800	35,900	0.7
Aged 100 hr, 400 F	10.5	37,950	37,100	0	400	9.8	36,500	31,425	1.0
Aged 100 hr, 500 F	9.0	36,620	27,100	0.5	500	7.7	26,385	20,850	2.3
Aged 100 hr, 600 F	8.0	30,150	20,900	1.0	600	8.3	18,430	14,700	4.5
Alloy 142-T6									
As heat treated	10.5	48,000	...	0	...	...	...	...	...
Aged 100 hr, 300 F	10.0	47,190	...	0	300	9.5	45,170	...	0
Aged 100 hr, 400 F	10.0	40,800	...	0	400	8.3	36,980	...	0
Aged 100 hr, 500 F	9.0	32,830	...	0	500	8.5	25,200	20,870	0
Aged 100 hr, 600 F	8.8	26,500	15,500	1.7	600	8.3	14,400	10,000	12.0
Alloy XA140-T2									
As heat treated	...	28,400	23,570	0.8	...	...	...	...	...
Aged 100 hr, 400 F	...	25,700	23,430	0	400	...	31,100	22,600	1.2
Aged 100 hr, 500 F	...	33,300	23,200	1.5	500	...	28,200	19,940	1.8
Aged 100 hr, 600 F	...	31,300	21,870	0.5	600	...	19,780	14,080	17.0

(a) All specimens tested at elevated temperature were held at the indicated temperature of testing for 100 hr.

Table XVIII. Comparison of Tensile Properties of Specimens Cut from Production Sand Castings and As-Cast Test Pieces

Foundry	As-Cast Test Bars			Test Bars from Production Castings		
	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 In., %	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 In., %
Alloy 355-T6						
A	36,160	28,760	2.3	30,645	24,100	2.5
B	36,160	28,000	2.2	30,315	20,910	1.0
Alloy 355-T51						
A	26,600	...	1.0	20,500	...	0
B	26,430	...	1.0	21,700	...	0
A	27,750	...	2.0	23,770	...	1.4
B	26,900	...	2.0	24,506	...	1.0
Alloy 355-T71						
A	33,600	29,350	1.3	27,700	...	0.4
Alloy 356-T6						
A	35,800	29,500	3.9	27,980	24,250	1.5
B	36,400	30,100	4.0	31,950	25,250	4.0

A considerable scatter in tensile and yield properties occurs in both separately cast test specimens and those cut from production castings. Reproducibility of results is somewhat less in fatigue testing of both smooth and notched specimens. Neither impact nor fatigue properties are used in acceptance specifications. The range of fatigue strengths for most of the sand and permanent mold casting alloys is shown in Fig. 18. Because of the scatter, even in tests made on the same alloy, cast with identical procedures, the bands shown in Fig. 18, can probably be considered typical of most cast alloys. No alloy or group of alloys could be selected for use strictly on the basis of a consistent superiority in fatigue resistance, as determined on standard fatigue specimens.

Data from test bars, particularly for die castings, should not be seriously considered in design analyses for applications requiring resistance to dynamic loading. The fatigue strength of cast aluminum is markedly dependent on the casting process, the soundness of the casting and whether or not the area that is subject to fatigue has been machined.

Actual fatigue testing of fully machined parts is the only method of alloy or process selection. One such example is a clutch torque-shaft. A maximum load for actual service was determined for this part and the necessary life-cycle was assigned. Die cast and permanent mold cast parts were made and fatigue tested. Figure 19 shows the tested part (note the typical "X" fracture common to fatigue failure) and the fatigue curves for the part as a permanent mold casting and as a die casting. Despite the fact that published fatigue strength values for as-cast test specimens of the die casting alloy (A380) are virtually twice as high as those of the permanent mold casting alloy (319), the selected die cast part had lower fatigue strength than the part made by permanent molding.

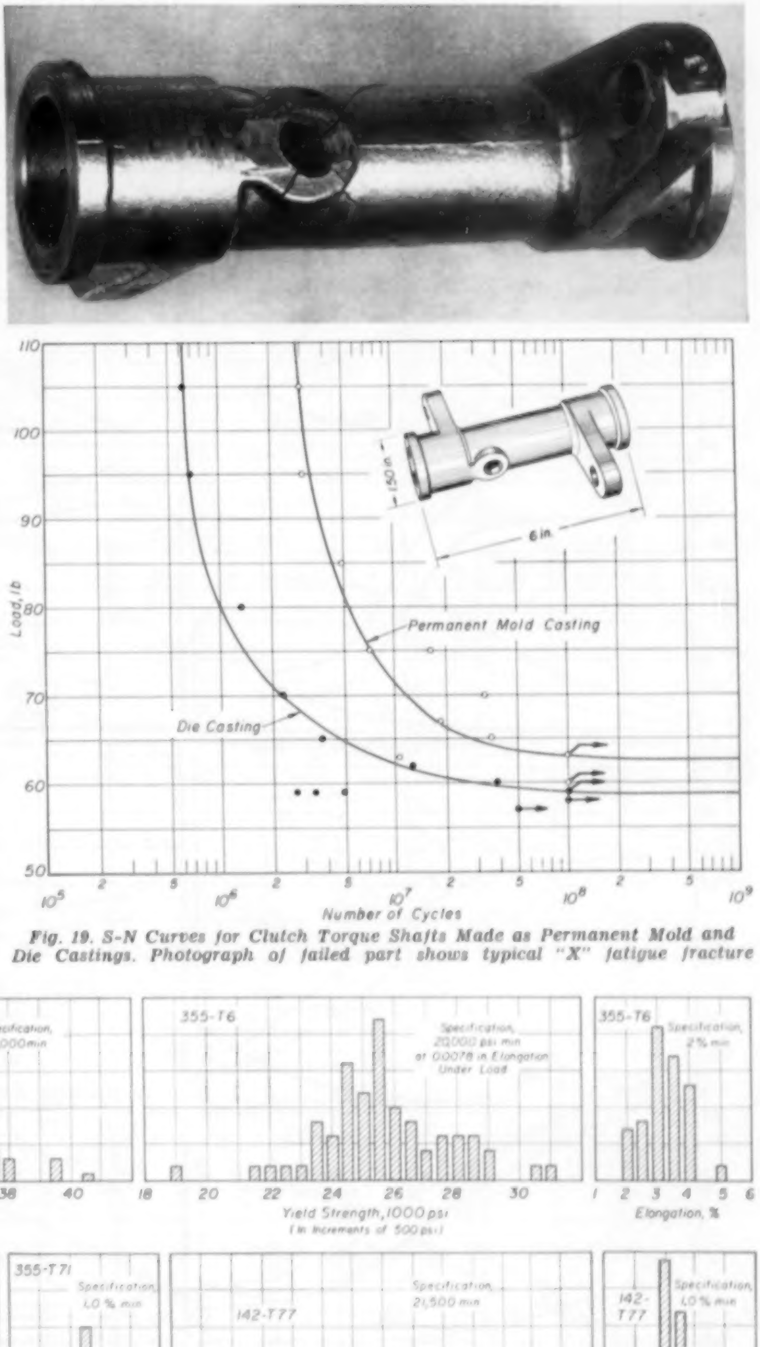


Fig. 19. S-N Curves for Clutch Torque Shafts Made as Permanent Mold and Die Castings. Photograph of failed part shows typical "X" fatigue fracture

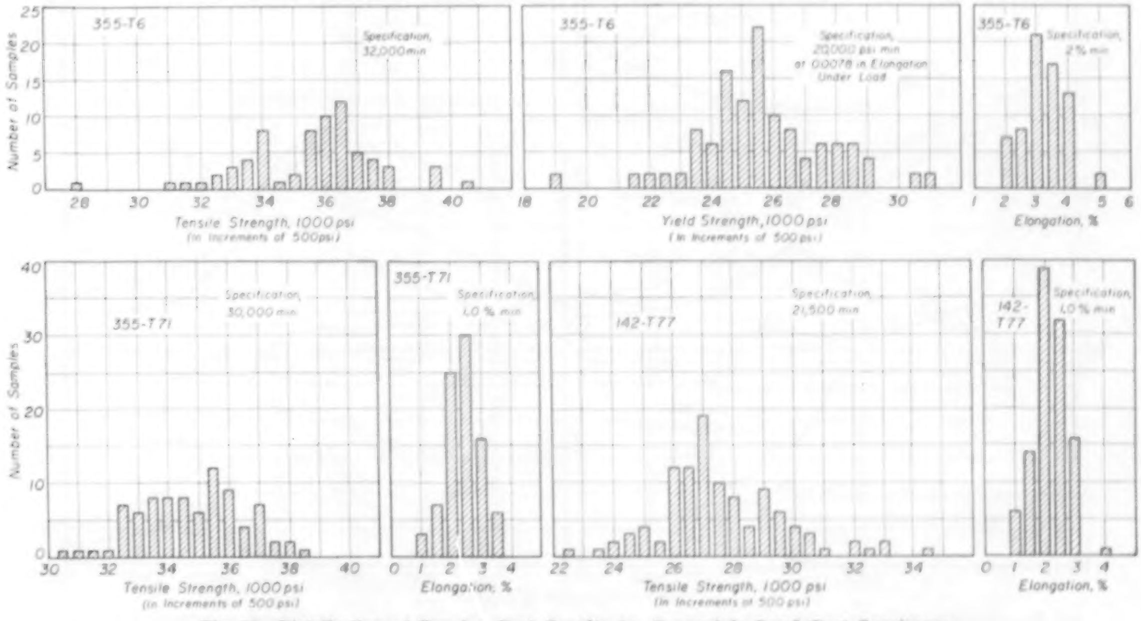


Fig. 20. Distribution of Tension Test Results for Separately Sand-Cast Specimens

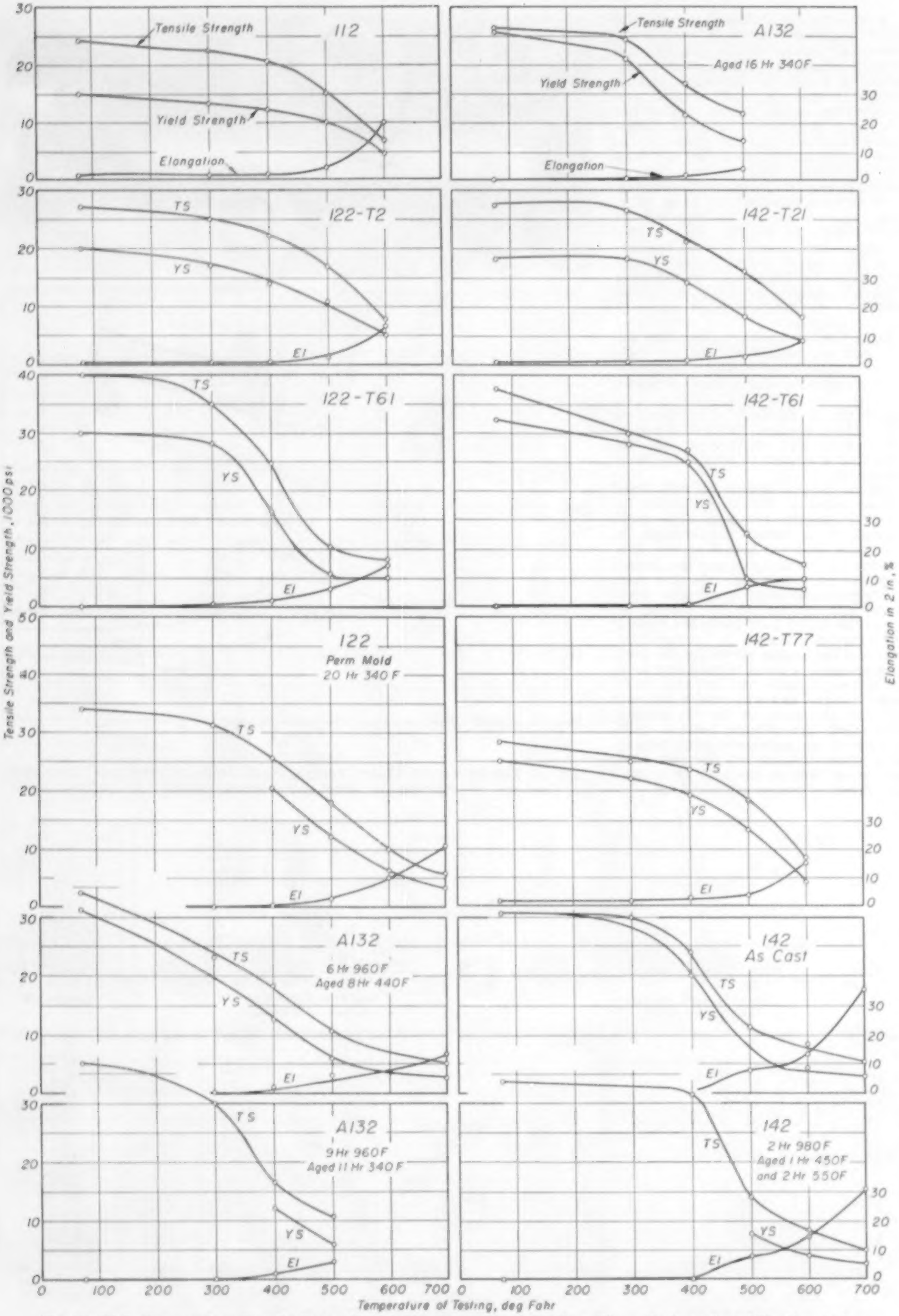
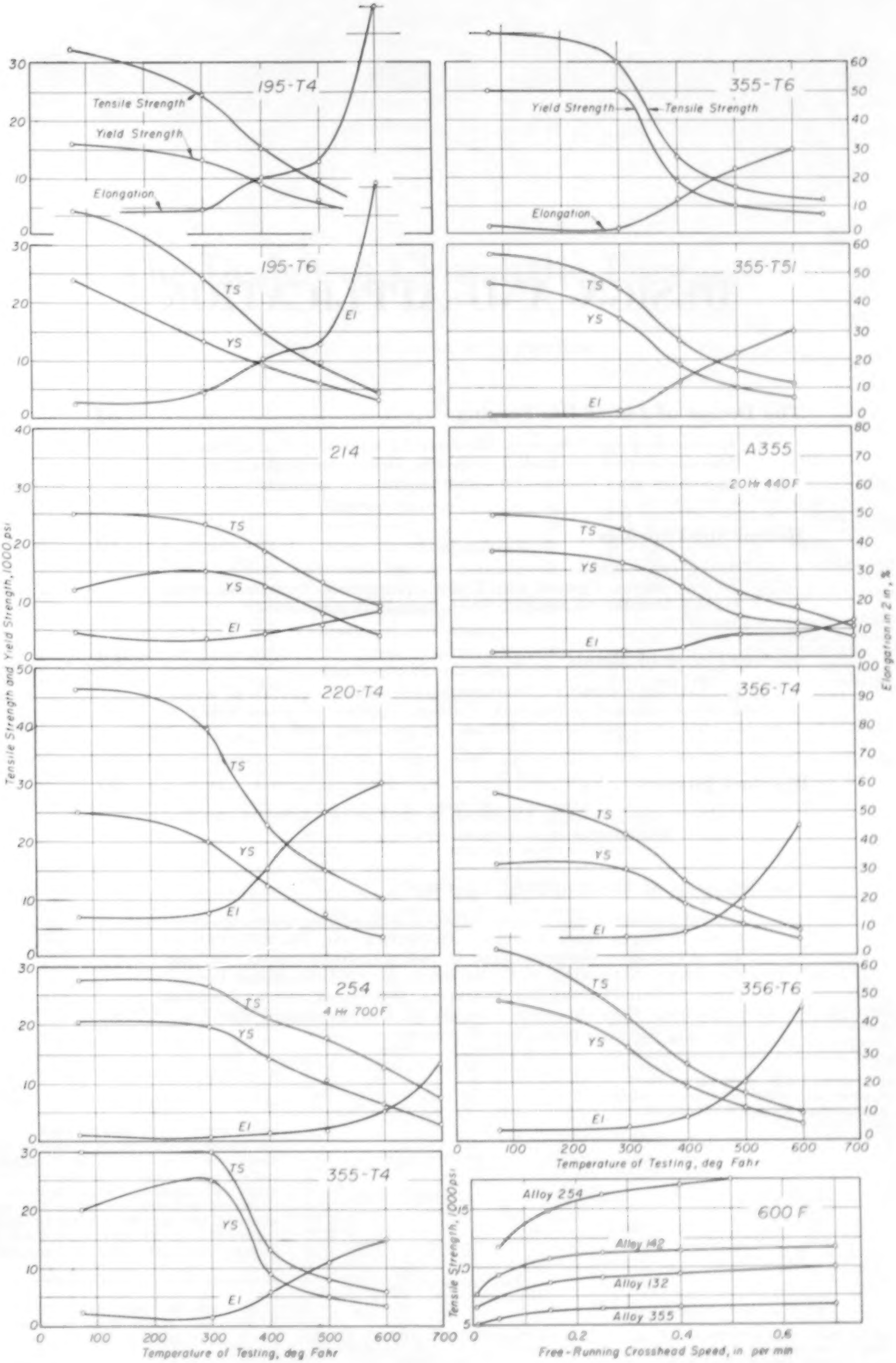


Fig. 21. High-Temperature Tensile Properties of Aluminum Sand Casting Alloys. Prolonged stabilization before testing (10,000 hr at testing temperature) Data are continued on the next page.


195-T4
Tensile Strength
Yield Strength
Elongation
355-T6
Yield Strength
Tensile Strength
Elongation
195-T6
TS
YS
El
355-T51
TS
YS
El
214
TS
YS
El
A355
20 Hr 440 F
TS
YS
El
220-T4
TS
YS
El
356-T4
TS
YS
El
254
4 Hr 700 F
TS
YS
El
356-T6
TS
YS
El
355-T4
TS
YS
El
Tensile Strength and Yield Strength, 1000 psi
Elongation in 2 in., %
0
100
200
300
400
500
600
700
Temperature of Testing, deg Fahr
600 F
Alloy 254
Alloy 142
Alloy 132
Alloy 355
Tensile Strength, 1000 psi
5
10
15
0
0.2
0.4
0.6
Free-Running Crosshead Speed, in. per min

DESIGN AND APPLICATION

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The Design of Closed-Die Forgings

By the ASM Committee on Forgings

FORGING is the process of working hot metal between dies, usually under successive blows and sometimes by continuous squeezing. Closed-die forgings or "drop forgings", hot upset parts, and extrusions are shaped within a cavity formed by the closed dies.

According to the Drop Forging Association, 385 million carbon steel forgings with a total weight of 674,000 tons and an average weight of 3½ lb were made in 1953. Comparative figures for forgings of all other metals in the same period were 104 million forgings, 299,000 tons and 5¾-lb average weight. Forgings weighing 1 lb or less constituted 45% of all forgings made; those weighing from 1 to 2 lb totaled 27½%, and heavier forgings made up progressively smaller percentages. Board hammers and air lift hammers made 448 million forgings; upsetters, 97 million; steam hammers, 60 million; and forging presses, 21 million.

Hammer Forgings

Many small forgings are made in a die that has successive cavities to preshape the stock progressively into its final shape in the last or "finish" cavity. Dies for large forgings are usually made to perform one operation at a time. The upper half of the die, having the deeper and more intricate cavity, is keyed or dovetailed into the hammer ram. The lower half is keyed to the "sow block" or bed of the hammer in precise alignment with the upper die. After being heated, the forging stock is placed in one cavity after another and is thus forged progressively to the final shape.

The Parting Line is the plane along the periphery of the forging where the striking faces of the upper and lower dies come together. Usually the die has a gutter or recess just outside the parting line to receive overflow metal or flash forced out between the two dies in the finish cavity (Fig. 1). More complex forgings may have other parting lines around holes and other contours within the forging that may or may not be in the same plane as the outer parting line.

Supplements the articles on pages 36 to 42 of the 1948 ASM Metals Handbook

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For greatest economy, the outer parting line should be in a single plane. When it must be along a contour, either step or locked dies may be necessary to equalize thrust, as shown in Fig. 2. This may increase costs as much as 20% because of the increased cost of forging and trimming dies and processing difficulties in forging and trimming. Sharp steps or drops in the parting line should be limited to about 15 deg from the vertical in small parts and 25 deg in large forgings, to prevent a tearing instead of a cutting action in trimming off the flash. Locked dies may be avoided sometimes by locating the parting line as shown in the lower sketch of Fig. 3.

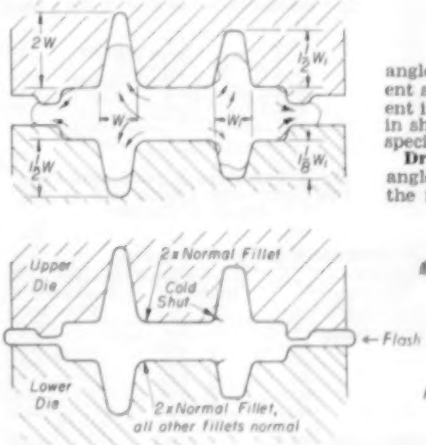

Fig. 1. Two Stages in Completion of a Forging. Top: Limitations on height of rib

The specification of optional parting lines on forgings to be made in different shops allows the parting lines to vary from shop to shop. Unless the draft has been removed, this variation in parting may cause difficulties in locating forgings when they are being chucked for subsequent machining. However, shearing the draft is not always an adequate remedy if trimming angles vary. Forgings made in different shops are likely to be more consistent in quality and to have less variation in shape when a definite parting line is specified.

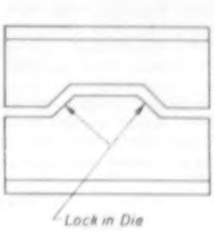

Fig. 2. Locked Dies

Draft on the sides of a forging is an angle or taper necessary for releasing the forging from the die and is desir-

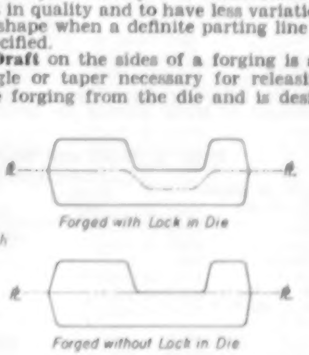

Fig. 3. Orientation of a Forging in the Die to Avoid Counterlocked Dies and to Eliminate Draft

able for long die life and economical production. Draft requirements vary with the shape and size of the forging. The effect of size on the amount of metal needed is illustrated by Fig. 4.

"Inside draft" is draft on surfaces that will tighten on the die as the forging shrinks during cooling; examples are cavities such as narrow grooves or pockets. "Outside draft" is draft on surfaces such as ribs or bosses that shrink *away from* the die during cooling. Both are illustrated in Fig. 5, which shows inside draft greater than outside draft—the usual relation. Recommended draft angles and tolerances are given in Table I.

Increased draft, called "blend draft" or "matched draft" may be needed on a side that is not very deep below the parting line, in order to blend with a side of the forging of greater height above the parting line, as shown in Fig. 6. Increased draft is sometimes desirable or required in locked dies to strengthen the dies or trimmer so as to reduce breakage and cost. Often this can be anticipated by sketching the die needed to shape a given forging. Cylindrical, spherical, square, rectangular and some irregular sections can be forged without draft when the parting line is specified as shown in Fig. 7, but with some additional risk of breakage of dies. Other parts, such as the ends of cylinders, may be forged in locked dies at an angle so as to avoid draft on the ends.

Ribs and Bosses. Forgings that have ribs or bosses at or near the maximum heights recommended in Fig. 1 are usually forged at temperatures (2250 to 2300 F) higher than normal to insure flow of the metal into the die cavities. Ribs are more readily formed in the upper die where the temperature is higher; the lower die extracts heat from the forging, which is in continuous contact with it. The ribs formed by the upper die will have better surface quality than those in the lower die because scale left by the part is more easily removed.

ASM Committee on Forgings

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Wyman-Gordon Co.

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AmForge Div.
American Brake Shoe Co.

ADOLPH KASTELOWITZ
Chief Manufacturing Engineer
Republic Aviation Corp.

GEORGE MCKEOWN
General Superintendent
Moore Drop Forging Co.

JOHN A. WEBBER
Chief Metallurgist
Interstate Drop Forge Co.

The maximum height of a rib depends on its width at the base and on blocking operations that preshape the stock. Fillets of minimum size cannot be used at the base of a rib of maximum height if the rib is to be sound and completely filled. Twice the minimum fillet size should be used; a full radius is preferable at the crest of the rib; and draft should be increased if possible.

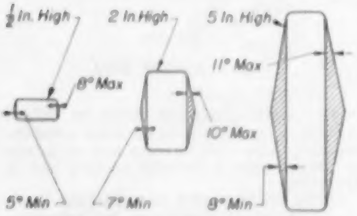


Fig. 4. Effect of Part Size on the Amount of Metal Needed for Draft

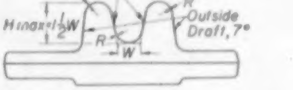


Fig. 5. Definition of Inside and Outside Draft and Limitations on the Depth of Cavities

Table I. Draft and Draft Tolerances for Steel Forgings

Height or Depth of Draft, in.	Commercial Standard		Special Standard	
	Draft, deg	Tolerance,(a) Plus, deg	Draft, deg	Tolerance,(a) Plus, deg
Outside Draft				
¼ to ½	...	...	3	2
¼ to 1	5	3	...	...
Over ½, up to 1	...	...	5	2
Over 1, up to 3	7	3	5	3
Over 3	7	4	7	3
Inside Draft				
¼ to 1	7	3	5	3
Over 1	10	3	10	3

(a) The minus tolerance is zero.

Fillets and Radii. In forging, some radii will wear and grow greater; others will become sharper under the combined effects of the pressure of repeated hammer blows and abrasion.

Radii that are too small give the forge die a shearing action and develop high resistance to the flow of the metal, thus increasing die wear and reducing the life of the die. Radii should be as large as the design will permit. Sharp radii in a forging die set up strains that cause the die to check, thus reducing die life and increasing the cost. Very little material can be saved by producing a design that includes sharp internal (fillet) radii.

The effects of small and large radii are illustrated by Fig. 1, which shows a forging during two stages of the operation. In small steel forgings (less than 2 lb) ⅛-in. radii in fillets are considered the absolute minimum. Common practice is to make the fillet radii twice the size of the corner radii. These radii will increase in proportion to the size and weight of the forgings, as shown in Fig. 8. For steel forgings of average size (3 to 8 lb), ¼-in. fillet radii are normal.

When alloys such as nitralloy or stainless steel are being forged, special consideration must be given to transition radii, and a ¼-in. fillet radius is the absolute minimum.

Recommended fillet and corner radii for various heights of rib or boss are given in Fig 9.

Holes and Cavities. Holes should not obstruct the natural flow of the metal in the forging operation. If cavities lie perpendicular to the directional flow of metal, it may be necessary to add breakdown or blocking operations on the forging billet before it is placed in the dies for forging. Such operations add cost and must be justified economically. In almost all instances where a hole is to be punched, a forged cavity will be provided to displace the metal in order to relieve the work load of the punch in the later operation. Holes and cavities should not be higher or deeper than the base of the widest cross section when normal fillets and radii are used. If a full radius or a hemispherical shape is allowed at the bottom of a cavity, the maximum depth of the cavity may be 1½ times the width (the diameter) as shown in Fig. 5.

On shallow cavities a draft angle of 7 deg and the required normal radii can be used. On cavities of maximum depth the draft should be increased to 10 to 12 deg.

Minimum Web Thickness. The web in a forging is limited to the thickness at which it gets too cold before forging

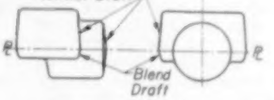


Fig. 6. Normal Draft and Blend Draft

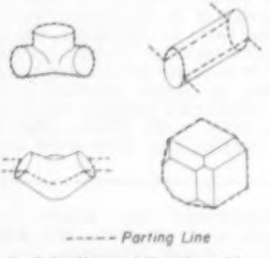


Fig. 7. Selection of Parting Lines to Eliminate Draft

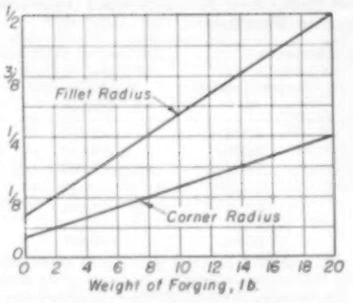


Fig. 8. Minimum Fillet and Corner Radii for Steel Forgings

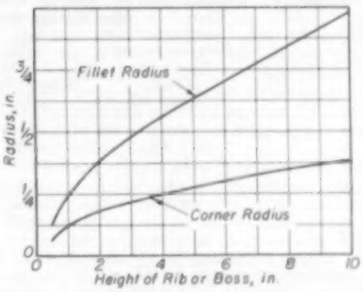


Fig. 9. Height of Rib or Boss in Relation to Fillet or Corner Radius

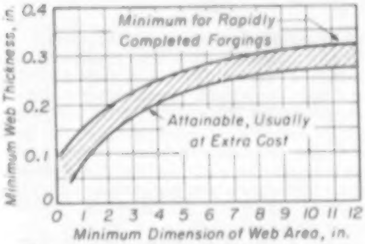
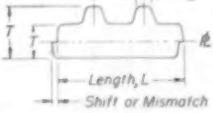


Fig. 10. Recommended Minimum Web Thickness in Relation to Minimum Dimension of Web Area

is completed. If the web gets cold enough in forging to look black, it will prevent the part from being brought down to size. Figure 10 shows the limiting minimum web dimension as a function of web size. The minimums shown are generally accomplished on various metals with more or less difficulty—particularly in a problem forging that requires more than a few blows for completion. Many web thicknesses that fall into the band between the two curves will be made only with difficulty and at extra cost; some that fall below the curve are regularly produced, whereas the web thicknesses that fall above the upper curve are almost always made without extra cost in forgings that can be completed rapidly.

When a web thinner than recommended is required, some advantage may be gained by tapering the web 5 to 8 deg toward the thinnest section, at the center, but average minimum thickness of web must be retained to meet strength requirements.

Lightening Holes in Webs. Holes are not always desirable as a means for reducing weight because of the effect on the strength of the part and because of stress concentration. Lightening holes are almost always produced by an added operation and the expense involved is often unjustified. These holes should be used only in neutral or low-stress areas, or to reduce cooling cracks and warpage caused by uneven cooling. Holes should be kept away from edges and should be provided with a strengthening bead to reduce stress concentration as shown in Fig. 11. A hole near the edge of a forging usually leaves inadequate material in the highly stressed area around the hole.



Definition of Dimensions Used in Tables II and III

Table II. Recommended Commercial Tolerances for Length of Steel Forgings

Maximum Length of Forging, in.	Tolerance on Length or Location,[a] in. Plus	Minus
6	0.047	0.031
15	0.062	0.047
24	0.125	0.062
36	0.125	0.062
48	0.125	0.125
60	0.187	0.125
72	0.219	0.125

(a) Relative location of ribs, holes or shoulders

Tolerances

Forging tolerances, based on area and weight, which represent good commercial practice are listed in Tables II and III. These tolerances apply to the dimensions shown in the illustration accompanying the tables. In using these tables to determine the size of the forging, the related tolerances such as mismatch, die wear and length should be added to allowance for machining plus machined dimensions. On the average, tolerances listed in Tables II and III conform to the full process tolerance of actual production parts and will yield more than 99% acceptance of any dimension specified from this table. In particular, as shown in Table IV, instances may be found of precise accuracy or rarely as much as ±50% error in the tolerances recommended in Table III. The values in Table IV represent the product of a die for one run and not the full range of product between successive resinkings of the die.

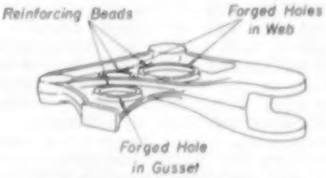


Fig. 11. Lightening Holes in a Forging

Shift or Mismatch Tolerance allows for misalignment of dies during forging, as shown in Fig. 12. All angular or flat surfaces of the die will erode or wear away and increase the volume of the forging, depending on the extent to which the forged metal flows over them. This increase is called "spread" or die wear, which must be included in the forging dimensons.

The characteristics of die wear are shown graphically in Fig. 13. The part represented was made of 4140 steel, using 10 blows in a 2500-lb board hammer. Tolerances were commercial standard, and the part was later coined to a thickness tolerance of +0.010 in., −0.000. The die-block, 10 by 18 by 18 in., was hardened to Rockwell C 42. After 30,000 forgings had been produced, the die wore as indicated, and the dies were resunk.

A range of tolerance is given for mismatch in Table III. The higher val-

Table III. Recommended Commercial Tolerances for Steel Forgings

Forging Size		Tolerance, in.			
Area, sq in.	Weight, lb	Thickness, Plus	Thickness, Minus	Mismatch, Plus	Die Wear, Plus
5.0	1.0	0.031	0.016	0.016 to 0.031	0.031
7.0	7.0	0.062	0.031	0.016 to 0.031	0.062
10.0	1.5	0.031	0.031	0.016 to 0.031	0.031
12.0	12.0	0.062	0.031	0.016 to 0.031	0.062
20.0	2.0	0.062	0.031	0.016 to 0.031	0.062
20.0	30.0	0.062	0.031	0.020 to 0.040	0.062
38.0	4.5	0.062	0.031	0.016 to 0.031	0.062
38.0	80.0	0.062	0.031	0.025 to 0.050	0.062
50.0	8.0	0.062	0.031	0.020 to 0.040	0.062
50.0	60.0	0.062	0.031	0.020 to 0.040	0.062
50.0	100.0	0.062	0.031	0.025 to 0.050	0.062
95.0	11.0	0.062	0.031	0.020 to 0.040	0.062
132.0	17.0	0.062	0.031	0.025 to 0.050	0.062
166.0	73.0	0.094	0.031	0.030 to 0.060	0.094
175.0	150.0	0.094	0.031	0.030 to 0.060	0.094
201.0	40.0	0.062	0.031	0.025 to 0.050	0.062
240.0	51.5	0.094	0.031	0.030 to 0.060	0.094
250.0	250.0	0.094	0.031	0.030 to 0.060	0.094
265.0	60.0	0.094	0.031	0.030 to 0.060	0.094
275.0	65.0	0.125	0.031	0.047 to 0.094	0.125
300.0	75.0	0.125	0.062	0.047 to 0.094	0.125
300.0	350.0	0.094	0.031	0.030 to 0.060	0.094
375.0	450.0	0.125	0.031	0.047 to 0.094	0.125
415.0	306.0	0.125	0.062	0.047 to 0.094	0.125
525.0	750.0	0.125	0.062	0.047 to 0.094	0.125
900.0	1000.0	0.125	0.062	0.047 to 0.094	0.125

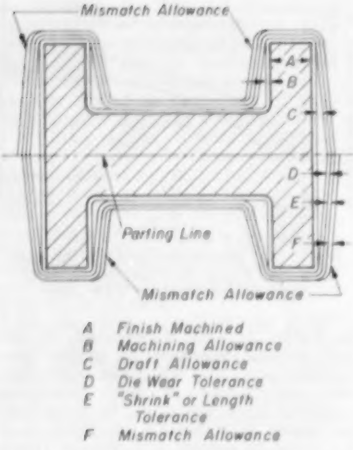


Fig. 12. Application of Tolerances and Allowances to Forgings. The dimensions are not to scale.

Table IV. Comparison of Quality Control Data with Recommended Tolerances for Seven Production Forgings

Part	Recommended Tolerance From Table III	Range of Observed Variation in Length for Specific Quality Control Limits 4σ	6σ	Difference Between Tolerance from Table III and 6σ Control Limit
A	0.094	0.042	0.063	+0.031
B	0.094	0.051	0.076	+0.018
C	0.094	0.060	0.090	+0.004
D	0.125	0.053	0.080	+0.045
E	0.125	0.081	0.122	+0.003
F	0.125	0.104	0.166	−0.041
G	0.125	0.111	0.166	−0.041

Values represent the product of a die for one run and not the full range of product between successive resinkings of the die. All tolerances are plus; negative tolerances, zero. Plus signs in the last column indicate the recommended tolerance is conservative compared with production experience.

Table V. Tolerance on Burr for Steel Forgings

Weight, lb	Trim Size,(a) in.		Tolerance, Plus,(b) in.
1	2	....	0.031
10	6	....	0.062
25	8	....	0.125
100	25	....	0.250

(a) The trim size refers to the greatest distance across the forging at the trim line. (b) The minus tolerance is zero.

Table VI. Draft Increment of Trim Tolerance for Steel Forgings

Height of Draft Face, in.		Tolerance Plus,(a) in.
¼	....	0.015
½	....	0.020
1	....	0.035
2	....	0.060
5	....	0.175
10	....	0.350

(a) The minus tolerance is zero.

ues are to be added to tolerances for forgings that need locked dies or involve side thrust on the dies during forging. On forgings that are heavier than 50 lb, it is sometimes necessary to grind out mismatch defects up to ⅛ in. max.

Length Tolerance in Table II refers to variations in shrinkage that occur when forgings are finished at different temperatures. Length tolerance should be applied to over-all lengths of forgings, as well as to the locations of bosses, ribs and holes.

Areas of a forging may be coined to hold closer tolerances, provided the metal is free to flow into an adjacent open area of the part. Under these circumstances, the tolerances shown in Fig. 14 can be held in production without difficulty. Over a hot sheared surface, the coining operation will bring the high points of the serrations within tolerance without removing all the depressions.

On the average, Table III represents full process tolerance. Figure 15 indicates the relationship of number of acceptable parts to the process tolerance. In application the full process tolerance must be derived from the process capability, the full value of which is represented on the chart as full process tolerance within which 100% (theoretically 99.7%) acceptability will result.

For a given process and tolerance, if the designer chooses to narrow the tolerance to two thirds of its full value, the acceptability will be reduced to 95%. Similarly a reduction to one third of the full tolerance would result in acceptability of 68%. Such reduction in tolerance incurs added expense because of the cost of rejected forgings and of 100% inspection to separate acceptable from rejected parts. Although it is possible to have a closer control of the forging process so as to increase the percentage of acceptable parts, the added control expense will also increase the cost of the parts.

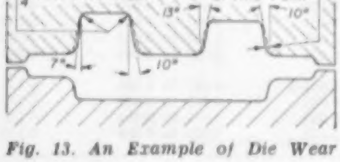


Fig. 13. An Example of Die Wear

Flash is trimmed in a press with a trimming die shaped to suit the plan view, outline and side view contour of the parting line. The forging may be trimmed with a stated amount of burr or flash left around the periphery at the parting line. It may be trimmed flush to the side face of the forging or some of the draft may be trimmed off, provided that the serrations or score marks left by the shearing operation are not an objectionable feature. In most commercial forgings some draft is sheared away.

Trimming Tolerance. When the trim must cut through the flash only and leave the side of the forging untouched, it is necessary to use a trim dimension that includes burr tolerance, mismatch, draft tolerance and die wear plus shrink tolerance. When it is satisfactory to trim draft partially, a closer trim tolerance may be held. Burr tolerance, listed in Table V, applies to the amount of flash that should remain between the side of the forging at the parting line and the outside edge of the trim cut.

Draft Tolerance depends on the height of the face having the draft, and applies to the dimension across the forging at the parting line. Draft tolerance (plus) is listed in Table VI for six different heights of the draft face on forgings.

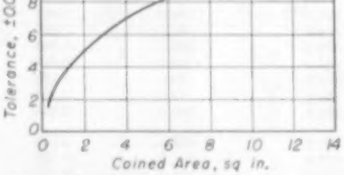


Fig. 14. Tolerances for Coining Unconfined Areas of Forgings

Die Wear Tolerance allows for an economical life of tools by providing for acceptability of parts after the die has made a quantity of pieces. The tolerance to be added to trimming tolerance and draft tolerance to allow for die wear is given in Table VII. The fourth part of the total tolerance is 0.003 in. per in. of greatest dimension across the forging at the trim line to be added as shrink tolerance.

The use of these tables may be illustrated by the following example: Assume a 5-lb forging 5 in. high and 5 in. across at the minimum shearing dimension. The tolerance is the sum of 0.045-in. burr tolerance plus 0.175-in. draft tolerance plus 0.040-in. die-wear tolerance plus 0.015-in. shrink tolerance, which equals 0.275-in. trim tolerance. Thus 5.275 in. is the largest dimension allowed for trimming when the side of the forging must not be cut and 5.000 in. is the smallest dimension to be allowed. This tolerance is most economical but in many forgings the tolerance can be held as close as shown in Table II by close control or extra operations.

Hot Shearing removes the draft from forgings with a vertical cut that improves dimensional accuracy and

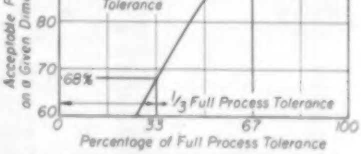


Fig. 15. Relation of Percentage of Acceptable Parts to Process Tolerance Specified on a Dimension

Table VII. Die Wear Increment of Trim Tolerance for Steel Forgings

Weight, lb	Trim Size,(a) in.	Tolerance, Plus,(b) in.
1	2	0.031
10	6	0.047
25	8	0.062
100	25	0.125

(a) The trim size refers to the greatest distance across the forging at the trim line. (b) The minus tolerance is zero.

leaves a serrated surface. This characteristic surface and accuracy is an economical preparation for machining, broaching, coining and accurate chucking in standard chucks. The surface is a substitute for rough machining or flame cutting.

The cheapest trimming operation on forgings is the cold trimming of small parts made from carbon steel of less than 0.50% C or from alloy steel of less than 0.30% C. However, to hot shear off about two thirds of the draft is economical because no special locating tools are required as for shearing off all the draft. The holes and outside of a forging can be sheared in one operation with a combination trimmer and punch in instances where the sheared burr of the holes and the outside are not required to be on opposite sides of the forging.

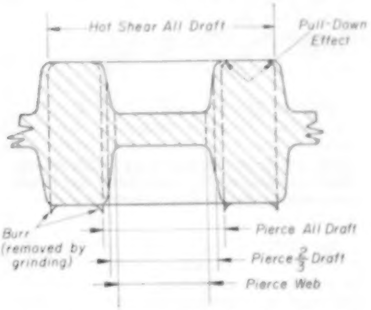


Fig. 16. Commonly Specified Hot Shearing Operations

The force of the shearing operation results in a rounded contour called "pull down" where the shear begins, and sharp burr edges on the opposite side of the forging where the shear ends, as shown in Fig. 16. The trimming and piercing forces are sometimes great enough to crush or distort the forging. For example, the force of piercing a hole in a thin-walled hub may expand the outside dimension if there is no outer flange to support it. If the wall has a flange around the outside, the piercing forces may crush the lower *ends* of the hub.

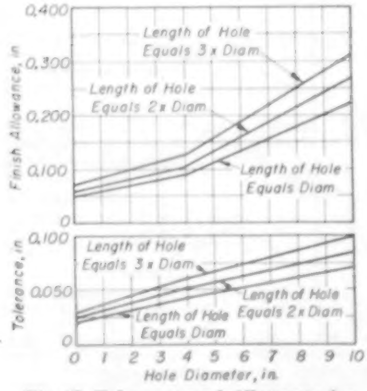


Fig. 17. Tolerance and Allowance for Hot Piercing of Holes to Be Broached

Piercing. Expansion may occur in hot piercing a hole in a cylindrical piece when the unsupported outside wall is 1.5 times the diameter of the pierced hole. All parts with an outside diameter only 1.2 times the pierced diameter will be distorted. In some parts in which the outer surface is sheared in the same operation that pierces the hole, an outside diameter 1.4 times the diameter of the hole may sometimes be used with good results, but generally for such parts 0.062 in. should be added to the end of the piece to allow for crushing of the ends if the ratio of outside diameter to inside diameter is less than 1.5. If the ratio is about 1.6, the allowance of 0.032 in. will be satisfactory, but for ratios of outside to inside diameter greater than 1.75 this allowance is seldom necessary.

Broaching Allowance. The amount of metal to be removed in broaching a hole in a forging may be controlled economically by hot piercing the hole to close tolerances or, less economically, by machining the hole before broaching. Figure 17 is a graph of the forging stock and tolerances to be allowed in a hole that is to be broached after hot piercing. In using the graph the allowance value at a given diameter is subtracted from the minimum broach diameter. This is the high limit for the size of the hot pierced hole. The hole dimension is then specified as the high limit with a tolerance of plus zero, minus the tolerance read from the graph.

Allowance for Machining

Surfaces that are to be machined must be forged oversize externally and undersize internally by an amount equal to the sum of applicable tolerances and machining allowance as shown in Fig. 18.

On machined surfaces parallel to the parting line, the stock allowance is affected by the tolerances for thickness and straightness. Machined surfaces perpendicular or nearly perpendicular to the parting plane are affected by the length tolerances, straightness and mismatch tolerances. The minimum machining allowance, set somewhat arbitrarily at 0.060 in. on small forgings and as high as 0.250 in. on large forgings, is given in Table VIII. The allowances shown are based on weight and shape, which are significant principally as an index of the amount of probable warpage. In all instances the depths of cut shown in the table will also remove permissible amounts of decarburization. The tolerance and allowance for hot piercing of holes that are to be broached is given in Fig. 17.

The precise effect of changes in section on the amount of distortion in heat treatment is not known. For small parts the usual method of overcoming distortion is by jig quenching or by marquenching.

Decarburization. Since the loss of carbon greatly lowers the resistance to fatigue, the decarburized skin should be removed by machining in highly stressed areas. Table IX shows the general limits for forgings of various sizes. The machining allowance is usually greater than the depths shown in Table IX.

Design for Tooling Economy. Considerable reduction in cost may result from forging designs that incorporate provisions for location of the forging for machining and inspection. Forgings that will be clamped to a face plate or a machine-tool table should be provided with three bosses under the proposed clamping points to locate the part and avoid both distortion and the tendency to rock (Fig. 19). When the quantity of parts is too small to justify tooling and holes are to be drilled instead of hot sheared in forging, the holes may be spotted with a cone angle steeper than the drill and about ½ to ⅔ of its diameter. This procedure

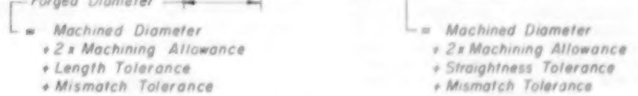
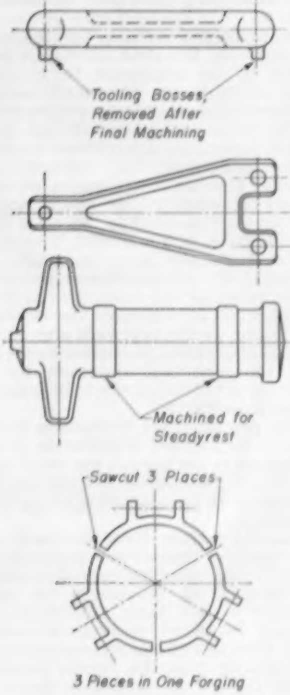


Fig. 18. Computation of Machining Stock Allowance

Table VIII. Machining Allowance on Each Surface for Average Steel Forgings

Maximum Weight of Forging, lb	Machining Allowance per Surface, in. Tall Forgings	Flat Forgings	Long Forgings
15	0.060 to 0.090	0.090 to 0.120	0.120
75	0.090 to 0.120	0.120	0.120
1000	0.120 to 0.190	0.120 to 0.250	0.190 to 0.250



Three Designs for Economy in Tooling

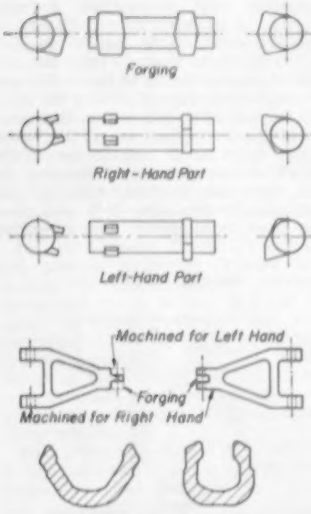


Fig. 19. (Above) Design for Economy in Tooling. (Below) Combination of right-hand and left-hand parts in the same forging. Bottom pair shows an unforgeable part that was bent to its final shape after preliminary forging.

Table IX. Typical Decarburization Limits for Steel Forgings

Range of Section Size, in.	Typical Depth of Decarburization, in.
Less than 1	0.031
1 to 4	0.047
4 to 8	0.062
More than 8	0.125

enables accuracy of locations comparable with length tolerances and squareness predictable from thickness tolerances if the part is not specially located for machining.

Long parts of irregular cross section that may have bow or camber should often be provided with steady rest locations in the forging design for economical machining as shown in Fig. 19. Machining economy and accuracy often result when a forging that presents a problem in machining is designed as a Siamese forging with multiple parts on the same forging to be saw-cut apart after machining.

Special opportunities for economy are present in the design of right-and-left-hand forgings to be transformed later as shown in Fig. 19. The method shown for avoiding right-and-left forging tooling should always be used for the manufacture of small quantities but may not be economical for large production. Figure 19 also shows a part that could not be forged without a secondary bending operation.

Cost of Forgings

Frequently the engineer is confronted with the problem of designing a steel part that may be produced either as a forging or a casting, each one equally capable of fulfilling the functional requirements. Usually the problem of which process to specify is answered ultimately on the basis of which allows the lower cost for the quantity desired. The higher cost of initial equipment for forging virtually eliminates forgings when quantities are low. As the quantity increases, there is a corresponding decrease in price, while with steel castings, because of higher scrap ratio, the decrease in price per piece diminishes as the quantity of castings increases. In Fig. 20 comparison is made of the relative costs of a 31½-lb brace made as a forging and as a steel casting.

The curve for the cost of casting is given in two parts: first with temporary pattern equipment having estimated life of approximately 200 pieces, and second as permanent equipment for more than 200 pieces. As shown by the graph, a quantity of 200 pieces is required in this example to justify the expense of forging dies. The cost of forging dies was approximately 3½ times greater than the temporary pattern equipment and 15% greater than the permanent pattern equipment.

For some parts, forging is the cheapest method of manufacture because of secondary operations that can be eliminated. An example is the cube in Fig. 7, with bevel edges that were required for weld clearance. The forging cost more than hack-sawed bar stock previously used in machining the part but the savings that resulted from elimination of the machining operation more than offset the cost added by forging.

Selection of Steel

The cost of steel as a percentage of the total manufacturing cost of forgings is shown in Fig. 21. These curves are based on an average of many actual forgings different in number of forging and heat treating operations required, cost of steel, quantity and setup cost. It should not be inferred from these data that an average 30-lb stainless steel forging will cost 34% more than an average 30-lb carbon steel forging.

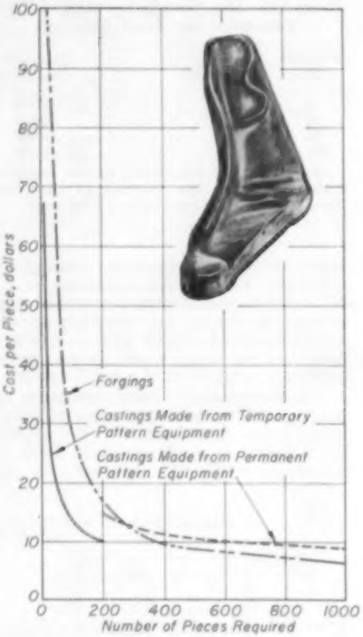


Fig. 20. Unit Cost of a 31½-Lb Brace Versus Quantity Required for Two Methods of Manufacture

Assuming a rating of 100% for the production attainable with the most forgeable steel, carbon steels gradually decrease in rating from 100% for 0.35% C to 75% for 0.95% C. The ratings for free-machining steels decrease almost proportionally with increasing carbon content, from 98% for C1117 to 93% for C1141, with the exception that B1112 and C1120 have a rating of 100% for attainable production.

Ratings for alloy steels range from 94% for those with the least hardenability to 77% for those with the greatest. Types 410, 416 and 420 stainless steels rate 67%, type 302 rates 60% and type 304, 55%.

Mechanical Properties

In rolled and forged parts, an etched surface has the appearance of fibers similar to those found in wood. In

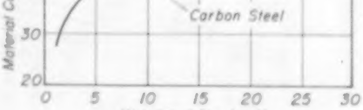


Fig. 21. Cost of Steel as a Percentage of Total Cost of Forgings

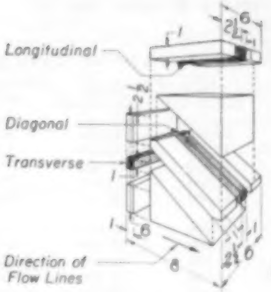


Fig. 22. *(Left) Location and Orientation of Specimens for Table X*

Table X. Effect of Orientation of Test Specimen on Mechanical Properties of Steel Forgings, with Specimen Locations as Shown in Fig. 22 at Left

Orientation	Yield Strength, psi	Tensile Strength, psi	Elongation in 2 in., %	Reduction of Area, %	Brinell Hardness
		Steel 5046			
Longitudinal	85,000	119,000	25.5	64.1	255
Diagonal	82,000	119,000	22.5	52.0	255
Transverse	87,000	119,500	11.5	20.5	262
		Steel 4340			
Longitudinal	146,000	159,000	19.0	54.5	341
Diagonal	144,500	158,000	17.5	49.3	331
Transverse	144,500	158,750	13.5	29.9	341

forgings the fibers or flow lines should follow the contour of the part.

The influence of orientation of a tension test specimen on the mechanical properties of a forging is one reason why specifications often call for different minimums for longitudinal and transverse properties. Longitudinal tests are taken parallel to the flow lines, while transverse tests are taken at 90 deg to the direction of flow. Tensile strength is approximately the same in both directions but elongation and reduction in area are usually better for a longitudinal bar.

Table X shows test results of tensile specimens for two different kinds of steel taken from a heat treated forging.

In another study of these directional effects on 4340 and 4330 modified steel, at different strength levels, large closed-die forgings of approximately 12-in. diam and 4 ft long were bored to leave a 1⅛ to 1½ in. wall thickness and then were heat treated. These forgings had been formed from a 15-in. square billet by a 5000-lb blacksmith hammer, a 25,000-lb blocking hammer, and a 35,000-lb finishing hammer.

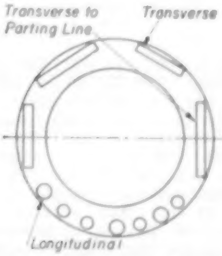


Fig. 23. *Location and Orientation of Specimens for Table XI*

Three sets of specimens were cut as illustrated by Fig. 23. One set was longitudinal or parallel to the forging axis; another set was transverse or normal to the forging axis away from the parting line; and the third set was vertical across the parting line with the critical section in the center of the parting line region. Results of tests summarized in Table XI show differences in properties resulting from orientation. Such differences can be expected in all forgings regardless of the steel used or its strength after being heat treated.

A total of 7 tensile, 10 notch-tensile, 15 impact, and 5 bend specimens were tested for each steel, in each orientation. Standard 0.505-in. round tensile specimens were used. Notch-tensile specimens of 0.300-in. nominal outside diameter had a circumferential 60-deg V-notch that removed 50% of the section area. The root radius of the notch was less than 0.001 in. Bend specimens of 0.4375-in. diam were 5⅝ in. long. The restricted bend method was used in which the specimen is supported at each end and the load is applied at the center of the specimen.

Design Stress Calculations

In a hand-operated gear-shifting lever mechanism, field performance was generally satisfactory, but some fatigue failures occurred in the ⅛-in. radius shown in Fig. 24. The lever is pivoted in a ball socket and the maximum load transmitted at end *A* is 400 lb. The steel is 1049 hardened to Brinell 269 to 285 with properties shown in Table XII.

As a simple lever, the stress at section 1 would be calculated as follows:

$$\text{Bending Moment} = M$$
$$= (\text{Force at } A)\ (\text{Lever Arm})$$
$$= (400)\ (6.25) = 2500 \text{ lb-in.}$$
$$\text{Stress} = \frac{\text{Bending Moment}}{\text{Section Modulus}}$$
$$= \frac{2500}{(0.0982)\ (\text{Diam})^3}$$
$$= \frac{2500}{(0.0982)\ (0.875)^3}$$
$$= 38{,}000 \text{ psi}$$

Since an abrupt change in size occurs at section 1, a stress concentration factor must be applied. This value is obtained from Fig. 25. Values applied to the curves are: From the dimensions in Fig. 24, $r = 0.125$ in., $d = 0.875$ in. and $h = 0.187$ in. Therefore:

$$\frac{r}{d} = \frac{0.125}{0.875} = 0.143$$

and

$$\frac{h}{r} = \frac{0.187}{0.125} = 1.5$$

The stress-concentration factor for these values or r/d and h/r is $k_t = 1.52$, read from Fig. 25. Therefore the calculated mean stress would be (1.52) (38,000) = 57,760 psi. This stress is well below the yield strength (101,000 psi).

Table XI. Effect of Location and Orientation on Mechanical Properties of Specimens Cut from Production Forgings (See Fig. 23, Above Left, for Locations of Specimens in the Forgings)

Property	4340 at Rockwell C 41			4330 (mod) at Rockwell C 43			4330 (mod) at Rockwell C 48		
	Longitudinal	Transverse	Transverse to PL	Longitudinal	Transverse	Transverse to PL	Longitudinal	Transverse	Transverse to PL
				Tension Test with Standard Unnotched Specimens					
Tensile strength, psi	190,950	191,300	187,600	197,200	198,075	196,925	235,825	239,175	239,775
Yield strength, 0.2% offset, psi	179,500	181,000	176,125	183,250	184,200	183,750	203,000	203,250	205,875
Elongation in 2 in., %	14.6	8.2	4.6	14.5	11.0	6.3	10.0	7.9	3.2
Reduction of area, %	48.9	17.1	9.8	47.7	28.0	13.3	44.3	27.2	7.5
				Tension Test with Notched Specimens					
Notch strength at 68 F, psi	280,600	267,000	248,000	281,000	277,800	273,000	306,000	280,600	253,800
Notch strength at —65 F, psi	289,400	279,800	251,400	286,800	285,600	277,200	291,800	239,600	190,600
Notch ductility at 68 F, %	3.46	2.74	1.76	3.00	2.58	1.72	2.00	1.90	1.36
Notch ductility at —65 F, %	2.82	2.20	1.22	1.98	2.16	1.58	1.54	1.26	1.04
				Charpy Impact Test					
Charpy impact at 68 F, ft-lb	27.5	15.4	10.9	20.1	16.1	12.2	17.5	14.3	8.5
Charpy impact at 32 F, ft-lb	20.0	14.5	9.6	19.0	16.6	12.8	17.2	13.6	7.2
Charpy impact at —65 F, ft-lb	17.3	11.3	8.6	16.4	15.0	8.8	14.0	11.4	5.9
				Restricted Bend Test					
Bend load, lb	5570	5350	4710	5730	5520	4050	6600	6620	6110
Outside bend angle, deg	180	38	15	180	67	27	147	61	18

All values shown are averages. A total of 7 tensile, 10 notch-tensile, 15 impact and 5 bend specimens were tested for each steel. Standard 0.505-in. round tensile specimens were used. Notch-tensile specimens of 0.300-in. nominal outside diameter had a circumferential 60-deg V-notch that removed 50% of the section area. The root radius was less than 0.001 in. Bend specimens were 0.4375-in. diam by 5⅝ in. long.

The data were obtained with the restricted bend method in which the specimen is supported at each end and the load is applied at the center of the specimen.

However, the occurrence of failures under service conditions indicated the probability of fatigue.

To investigate actual stresses, a strain gage was installed in the radius, and observations made during operation revealed stresses in the range from 40,000 to 50,000 psi, but when gears were clashed, transient load impulses as long as 2½ sec in duration resulted in stress as high as 90,000 psi at a frequency of 80 cycles per sec. Thus about 200 stress reversals could occur several times during each hour the machine was in operation. This condition explains the possibility of the occurrence of 1,000,000 cycles in a few thousand hours of actual operation. It was necessary, therefore, to consider means of reducing the stress because of fatigue.

A draftsman's layout of the related parts revealed that the diameter could be increased to 1 in. and the radius to 0.187 in. Also, instead of the as-forged surface, it was expedient to machine the radius as shown in the following stress analysis (see lower part of Fig. 24).

In the previous formula, bending moment is unchanged, but the section modulus changes because of increased diameter. Then the stress after redesigning is:

$$\frac{\text{Bending Moment}}{\text{Section Modulus}} = \frac{2500}{(0.0982)\,(1)^3} = 25{,}400 \text{ psi}$$

In using Fig. 25,

$$\frac{r}{d} = \frac{0.187}{1} = 0.187$$

and

$$\frac{h}{r} = \frac{0.187}{0.187} = 1$$

Therefore the stress-concentration factor with the 0.187-in. radius would be reduced slightly, to 1.43, and the calculated mean stress after redesigning would be (1.43) (25,400) = 36,300 psi.

Life Expectancy. The foregoing computations have shown the calculated stresses for two different configurations at section 1. It was determined experimentally that peak stresses of 90,000 psi were observed in the original condition. The peak stresses with the enlarged diameter and radius will be reduced proportionally to the calculated stresses. Thus, the new peak stress would be

$$\frac{36{,}300}{57{,}700}\,(90{,}000) = 56{,}800 \text{ psi}$$

Table XII. Fatigue Strength of Heat Treated Wrought Steel of Various Hardness Ranges

Brinell Hardness Range	Nominal Tensile Strength, psi	Nominal Yield Strength, psi	Fatigue Strength at 1 Million Cycles, psi — Type of Surface: Ground	Machined	Hot Rolled	Forged
160 to 187	77,000	48,000	33,000	30,000	24,000	18,000
187 to 207	89,000	60,000	39,000	34,000	25,000	19,000
207 to 217	99,000	69,000	44,000	37,000	27,000	20,000
217 to 229	103,000	74,000	46,000	38,000	27,000	20,000
229 to 241	109,000	80,000	49,000	40,000	28,000	20,000
241 to 255	114,000	86,000	51,000	42,000	29,000	21,000
255 to 269	121,000	94,000	55,000	44,000	30,000	21,000
269 to 285	127,000	101,000	57,000	46,000	30,000	22,000
285 to 302	135,000	110,000	61,000	49,000	31,000	22,000
302 to 321	142,000	120,000	64,000	51,000	32,000	23,000
321 to 352	151,000	130,000	68,000	53,000	33,000	23,000
352 to 375	166,000	147,000	74,000	57,000	34,000	24,000
375 to 401	176,000	158,000	78,000	59,000	35,000	25,000
401 to 429	188,000	171,000	82,000	62,000	35,000	24,000
429 to 461	202,000	183,000	86,000	64,000	35,000	24,000
461 to 495	217,000	196,000	88,000	65,000	34,000	22,000
495 to 514	233,000	210,000	89,000	66,000	32,000	20,000
514 to 555	241,000	217,000	89,000	65,000	31,000	19,000

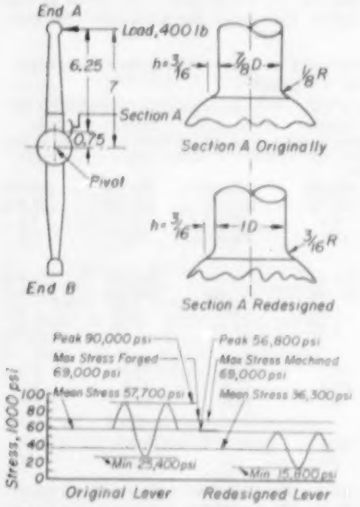


Fig. 24. (Above) Example Lever in a Problem of Redesigning; (Below) Plot of Stresses in the Original and Redesigned Part

The following discussion compares the effect of these maximum stresses on the life expectancy of the part.

In Fig. 26 the values for completely reversed cycles of stress for steel at a hardness range of 269 to 285 Bhn are plotted against life in cycles for surfaces as forged, hot rolled, machined and ground. The problem at hand concerns as-forged versus machined surfaces. The forged surface would be decarburized and subject to usual surface defects. At 1,000,000 cycles, as before, the allowable stress for a forged surface as read from Fig. 26 is 22,000 psi, whereas for the machined surface it is 46,000 psi — both considerably less than the yield strength (101,000 psi).

Figure 27 shows the relation between maximum stress and mean stress for forged and machined surfaces of the example part. At zero mean working stress (complete reversal) the values are the same as in Fig. 26 for 1,000,000 cycles. At the point in the upper right-hand corner of Fig. 27 where mean and maximum stresses are equal, the maximum stress and the mean stress are both equal to the tensile strength of the steel, and thus the load is static.

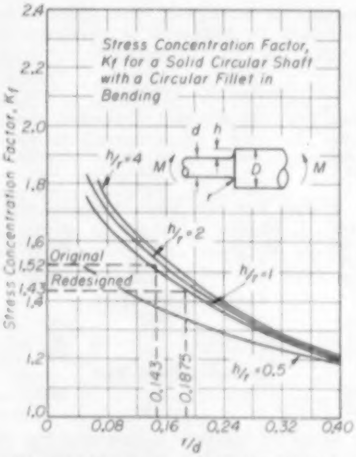


Fig. 25. Stress Concentration Factor for a Shaft with a Circular Fillet for Quenched and Tempered Steels (Bending)

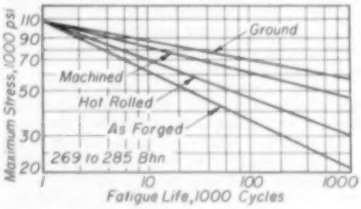


Fig. 26. Fatigue Strength for Steel of 269 to 285 Bhn with Ground, Machined, Hot Rolled and As-Forged Surfaces

In Fig. 27 the mean working stress of the original forging is represented by line 1, drawn from mean stress 57,700 psi vertically to its intersection with line 3 to predict a maximum stress of 69,000 psi for the forged surface, and drawn to its intersection with line 4 to predict a maximum stress of 82,000 psi for the machined surface. The stress of 82,000 psi is nearly equal to the maximum observed by strain-gage analysis and thus is indicative of failure.

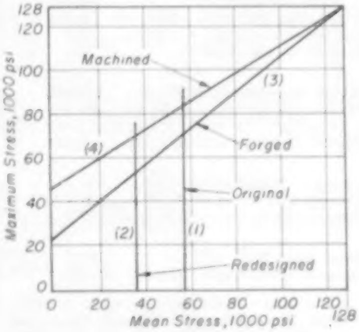


Fig. 27. Maximum Stress Versus Mean Working Stress for Steel with Forged and Machined Surfaces

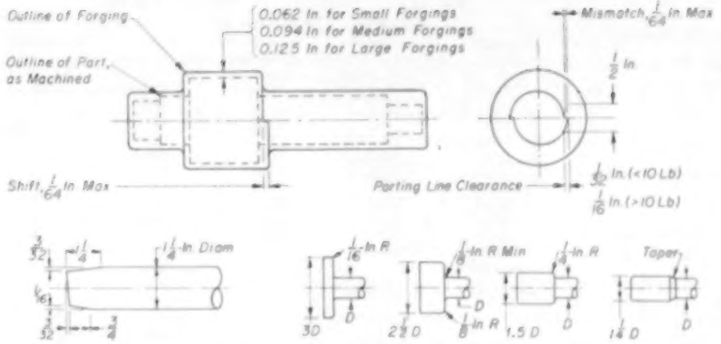

Outline of Forging
0.062 In. for Small Forgings
0.094 In. for Medium Forgings
0.125 In. for Large Forgings
Mismatch, 1/64 In. Max
Outline of Part, as Machined
1/2 In.
Shift, 1/64 In. Max
Parting Line Clearance
1/32 In. (<10 Lb)
1/16 In. (>10 Lb)
3/32
1/4
1 1/4-In. Diam
1/16
3/32
3/4
1/16-In. R
1/8-In. R Min
1/4-In. R
Taper
3D
D
2 1/2 D
D
1/8-In. R
1.5 D
D
1 1/4 D
D

Fig. 28 to 30. (Top, Fig. 28) Hot Upset Forging Terminology and Standards. (Left, Fig. 29) Probable Shape of Shear-Cut Ends. (Right, Fig. 30) Variation of Corner Radius with Thickness of Upset. These parts are the simplest forms of upset forgings.

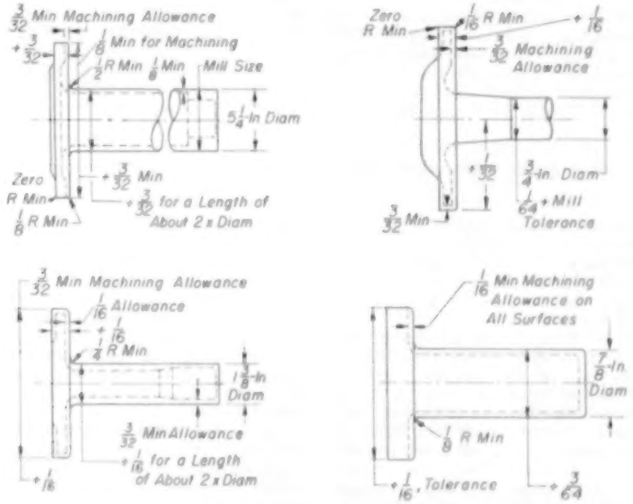

3/32 Min Machining Allowance
+3/32
1/8 Min for Machining
1/2 R Min
1/8 Min
Mill Size
5 1/4-In. Diam
Zero R Min
+3/32 Min
+3/32 for a Length of About 2 x Diam
1/8 R Min
Zero R Min
1/16 R Min
+1/16
3/32 Machining Allowance
+1/32
3/4-In. Diam
1/64 + Mill Tolerance
3/32 Min
3/32 Min Machining Allowance
1/16 Allowance
+1/16
1/4 R Min
1 3/8-In. Diam
3/32 Min Allowance
+1/16 for a Length of About 2 x Diam
+1/16
1/16 Min Machining Allowance on All Surfaces
7/8-In. Diam
1/8 R Min
+1/16, Tolerance
+3/64

Fig. 31. Tolerances (Shown with + or − Sign), Allowances and Design Rules for Upset Forgings

The vertical line 2 in Fig. 27 represents stresses in the redesigned forging for which the mean stress previously calculated is 36,300 psi. The values on the appropriate vertical line 2 of Fig. 27 show maximum working stresses of 52,000 psi for the forged surface and 69,000 psi for the machined surface.

The as-forged surface at 52,000 psi maximum working stress would not assure satisfactory life, since the recalculated maximum stress is 56,800 psi. However, the machined surface with a maximum working stress of 69,000 psi gives a safe margin above the 56,800 psi requirement for design stress. Interpreting these values, the forged surface should have a life expectancy of 1,000,000 cycles of stress. But since the load cycle was somewhat uncertain, the machined radius was chosen to obtain greater margin of safety. The foregoing discussion is diagrammed in Fig. 24 to show the values of calculated mean, peak, and minimum stresses in the problem on the original lever and the redesigned lever. Since the lever was redesigned no failures have occurred.

Table XIII. Length Tolerances for Unforged Stems of Upset Forgings

Maximum Length, in.	Minimum Plus Tolerance, in.
6	0.062
10	0.094
20	0.125
Over 20	0.156

Minus tolerance is zero.

Design of Hot Upset Forgings

Hot heading, upset forging or, more broadly, machine forging consists primarily of holding a bar of uniform cross section, usually round, between grooved dies and applying pressure on the end in the direction of the axis of the bar by using a heading tool so as to upset or enlarge the end into an impression of the die. The shapes generally produced include a variety of enlargements of the shank, or multiple enlargements of the shank and "re-entrant angle" configurations. Transmission cluster gears, pinion blanks, shell bodies and many other shaped parts are adapted to production by the upset machine forging process. This process produces a "looped" grain flow of major importance for gear teeth. Simple, headed forgings may be completed in one step, while some that have large, configured heads or multiple upsets may require as many as six steps. Upset forgings are produced weighing from less than 1 lb to about 500 lb.

Rules governing tooling for the upsetting of bar stock and tubing without injurious bending and cold shuts are given on page 40 in the 1948 Metals Handbook.

Machining Stock Allowances. The standard for machining stock allowance on any upset portion of the forging is 0.094 in., although allowances vary from 0.062 to 0.125 in. depending on size of upset, material and configuration of the part (Fig. 28).

Mismatch and shift of dies are each limited to 0.016 in. max. Mismatch is the location of the gripper dies with respect to each other as shown in Fig. 28. Shift refers to the relation of the dies to the heading tool.

Parting-line clearance is required in gripper dies for tangential clearance to avoid undercut and difficulty in the removal of the forging from the dies (Fig. 28).

Tolerances for shear-cut ends have not been established. Figure 29 shows a shear-cut end on a 1¼-in. diam shank. Straight ends may be produced by torch cutting, hack sawing or abrasive wheel cutoff at a higher cost than for sheared ends.

Corner radii should follow the contours of the finished part with a minimum of 1/16-in. radius. Radii at the outer diameter of the upset face are not required but may be specified as desired. Variations in thickness of the upset require variations in radii, as shown in Fig. 30, because the source of the force is farther removed and the die cavity more difficult to fill. When a long upset is only slightly larger than the original bar size, a taper is advisable instead of a radius.

Fillets can conform to the finished contour in most instances. The absolute minimum should be ⅛ in. on simple upsets, as shown in Fig. 30.

Tolerances for all upset forged diameters are generally + 1/16 in., − 0, except for thin sections of flanges and upsets relatively large in ratio to the stock sizes used where they are + 3/32 in., − 0. The increase of tolerances over the standard + 1/16 in., − 0 is sometimes a necessity, because of variations in size of hot rolled mill bars, extreme die wear or complexity of the part. Tolerances for unforged stem lengths are given in Table XIII.

Draft angles may vary from 1 to 7 deg, depending on the characteristics of the forging design. Draft is needed to release the forging from the split dies and also reduces the shearing of face surfaces during transfer from impression to impression.

For an upset forged part that requires several operations or passes, the dimensioning of lengths is determined on the basis of the design of each individual pass or operation.

Design of Specific Parts. A study of designs already being manufactured by the hot upset method of forging may serve as a guide for development of similar applications. The following examples illustrate some typical exceptions to general design rules.

It can be seen from Fig. 31 that the size of stock required to produce the part determines the allowances required for finish machining, thickness of upset, diameter tolerances, and corner

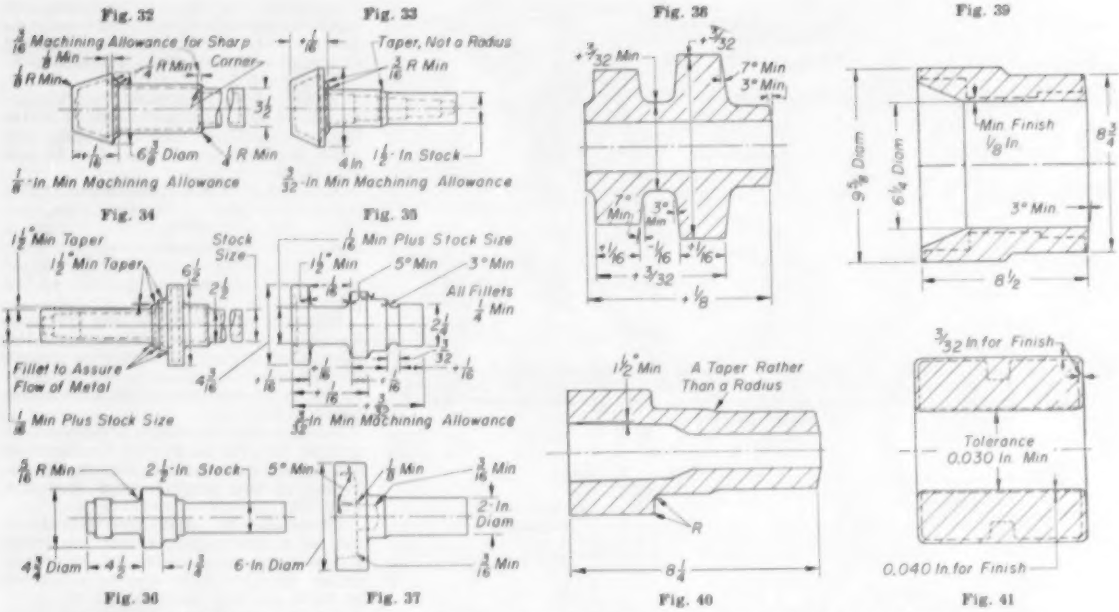

3/16 Machining Allowance for Sharp Corner
1/8 Min
1/4 R Min
1/8 R Min
3½
1/16
6 3/8 Diam
1/4 R Min
1/8-In Min Machining Allowance
1/8
Taper, Not a Radius
3/16 R Min
4 In
1½-In Stock
3/32-In Min Machining Allowance
1½° Min Taper
1½° Min Taper
Stock Size
6½
2½
Fillet to Assure Flow of Metal
4 3/16
1/16 Min Plus Stock Size
1/16 Min Plus Stock Size
1½° Min
5° Min
3° Min
All Fillets 1/4 Min
2¼
1/32
1/16
3/32-In Min Machining Allowance
5/16 R Min
2½-In Stock
4 3/4 Diam
4½
1 3/8
5° Min
1/8 Min
3/16 Min
2-In Diam
6-In Diam
3/16 Min
3/32 Min
3/32
7° Min
3° Min
7° Min
3° Min
1/16
1/16
1/16
3/32
1/8
9 5/8 Diam
6¼ Diam
Min Finish 1/8 In
8 3/4
3° Min
8½
1½° Min
A Taper Rather Than a Radius
R
8¼
3/32 In for Finish
Tolerance 0.030 In Min
0.040 In for Finish

Fig. 32 Fig. 33 Fig. 38 Fig. 39

Fig. 34 Fig. 35

Fig. 40 Fig. 41

Fig. 36 Fig. 37

Fig. 32 to 41. Tolerances (Shown with + or − Sign), Allowances and Design Rules for Upset Forgings

radii. The amount of upset stock required depends on bar size and determines whether the stock can be sheared, flame cut or torch cut, or separated by another method. Figure 30 illustrates a few of the simplest forms of upset parts.

Figure 32 shows a variation from the straight axle-shaft type of design where the beveled head of the upset is confined in the heading tool. This method usually requires that the design recognize a position in the forging where a flash or excess metal must be trapped between the dies and heading tool. This is indicated in Fig. 32 by the ⅛-in. min dimension. Another problem encountered in designs of the type shown in Fig. 32 is the filling of the barrel section at the point of transition from original stock size to slightly increased diameter. As noted, an additional amount for finish is required along with a generous radius.

Table XIV. Recommended Size Limitations for Hot Extrusions Made of Carbon and Alloy Steel

Inside Diameter, in.	Maximum Depth of Hole, in.	Outside Diameter Range, in.
7/16	2	9/16 to ¾
½	4	21/32 to 15/16
9/16	5	47/64 to 1 1/16
⅝	5½	13/16 to 1 5/32
11/16	5¾	⅞ to 1¼
¾	6	15/16 to 1⅜
⅞	6⅛	1 1/16 to 1 9/16
1	6¼	1 7/32 to 1 23/32
1½	6⅜	1¾ to 2¼
2	6½	2¼ to 3
2½	6⅝	2 25/32 to 3¾
3	6¾	3 5/16 to 4½
4	7	4⅜ to 5¾
5	7⅛	5 7/16 to 7
6	7¼	6 29/64 to 8¼
7	7⅜	7 15/32 to 9½
8	7½	8 31/64 to 10¾
9	7⅝	9½ to 12
10	7¾	10½ to 13¼

The same problem, shown in Fig. 33, can be overcome by a taper blending from the bar size to the shoulder diameters. This type of design is expedient where the two diameters are within ⅜ in. of each other.

Figure 34 is basically an axle-shaft type of forging with a long pilot. Since the pilot part of the forging must be carried in the heading tools, draft is required for withdrawal from the tool and usually should be no less than ½ deg. The length of the pilot determines the amount of draft, which may range to a maximum taper of 3 deg. Another design rule to be recognized is that the pilot diameter in the heading tool should be 1/16 in. larger than the bar diameter to allow the stock to bottom in the heading tool. Contingent on the number of passes required in producing the forging, plus the mill tolerance for the particular bar size, the pilot end diameter may require a maximum of ⅛ in. over the bar diameter.

Figure 35 illustrates a typical transmission cluster gear forging. The drafts specified are a requirement for this type of upset forging, since the part must be carried in the die after being partially produced. Of necessity, the neck diameter is determined by the stock size required to produce the part, plus an allowance to make a fit with the heading tool similar to that of Fig. 34.

Figure 36 shows a radius required when the pilot end must pass into the header. A small radius on the heading tool can scrape off metal along part of the length of the bar end and forge the loose chips into the face of the forged flange.

Figure 37 illustrates minimum tapers and radii required for depressions in upset forgings. A larger draft angle or radius, or both, decreases possibilities of cold shuts.

Figures 38 to 41 show variations of

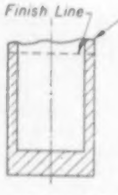

Finish Line
Excess Runout

Fig. 42. Straight Extrusion

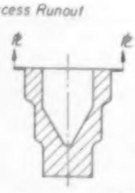


Fig. 43. Controlled Extrusion

Table XV. Tolerances for Straight Extrusions of Steel (See Fig. 44)

Weight of Forging, lb	Tolerance, Plus and Minus: Inside Diameter, in.	Tolerance, Plus and Minus: Outside Diameter, in.	Tolerance, Plus and Minus: Bottom Thickness, in.	Tolerance, Plus and Minus: Total Length, in.	Draft Tolerance: Outside Draft, deg	Draft Tolerance: Inside Draft, deg
0.2	0.005	0.005	0.010	+1/32	0 to 1	0 to 1
0.4	0.005	0.005	0.010	+1/32	0 to 1	0 to 1
0.6	0.005	0.005	0.010	+1/32	0 to 1	0 to 1
0.8	0.005	0.005	0.010	+1/32	0 to 1	0 to 1
1.0	0.006	0.006	0.012	+3/64	0 to 1	0 to 1
2.0	0.008	0.008	0.015	+3/64	0 to 2	0 to 2
4.0	0.010	0.010	0.020	+3/64	0 to 2	0 to 2
6.0	0.012	0.012	0.025	+1/16	0 to 2	0 to 2
9.0	0.015	0.015	0.031	+1/16	0 to 2	0 to 2
12.0	0.018	0.018	0.036	+1/16	0 to 3	0 to 3
15.0	0.020	0.020	0.040	+⅛	0 to 3	0 to 3
20.0	0.025	0.025	0.048	+⅛	0 to 3	0 to 3
30.0	0.030	0.030	0.060	+⅛	0 to 3	0 to 3

Table XVI. Tolerances for Controlled Extrusions of Steel (See Fig. 45)

Weight of Forging, lb	Tolerance, Plus and Minus: Inside Diameter, in.	Outside Diameter, in.	Bottom Thickness, in.	Total Length, in.	Nominal Draft: Outside Draft, deg	Inside Draft, deg
0.2	0.010	0.010	0.010	0.010	0 to 1	0 to 3
0.4	0.010	0.010	0.010	0.010	0 to 1	0 to 3
0.6	0.010	0.010	0.010	0.010	0 to 1	0 to 3
0.8	0.010	0.010	0.010	0.010	0 to 1	0 to 3
1.0	0.012	0.012	0.012	0.012	0 to 2	1 to 4
2.0	0.016	0.016	0.015	0.015	0 to 2	1 to 4
4.0	0.020	0.020	0.020	0.020	0 to 2	2 to 5
6.0	0.024	0.024	0.025	0.025	0 to 2	2 to 5
9.0	0.028	0.028	0.031	0.031	0 to 2	3 to 6
12.0	0.031	0.031	0.036	0.036	0 to 3	4 to 7
15.0	0.034	0.034	0.040	0.040	0 to 3	5 to 8
20.0	0.038	0.038	0.048	0.048	0 to 3	6 to 9
30.0	0.045	0.045	0.060	0.060	0 to 3	7 to 10

size and design of forgings that are pierced or punched. In such forgings the required finish for machining of the holes fluctuates from 0.040 to 0.080 in., according to size for parts that are to be broached. If the hole is machined, the standard amount of finish should be specified. This difference affects the final cost of the part.

In Fig. 38 the draft allowances required are similar to those of Fig. 35 to facilitate removal of the part from the die during and after forging. In Fig. 38 the large diameter shows a tolerance 1/32 in. larger than standard since the large flange that has been fabricated in the first pass must be carried in the die while the front flange is being upset. Carrying the flange from pass to pass requires clearance of the flange in the die, and as the punch enters the forging, there is some upsetting action of the back flange, creating a slight oval condition. The additional tolerance reflects not only die wear, but also ovality. This holds true for the neck diameter as well.

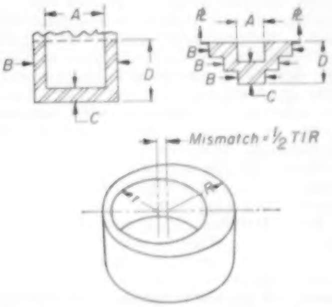


Fig. 44 to 46 (Above Left, Fig. 44) Dimensions Covered by Tolerances in Table XV. (Above Right, Fig. 45) Dimensions Covered by Tolerances in Table XVI. (Below, Fig. 46) Definition of Mismatch Tolerance in Terms of Total Indicator Reading for Values Given in Text (See Mismatch Tolerances, Last Column)

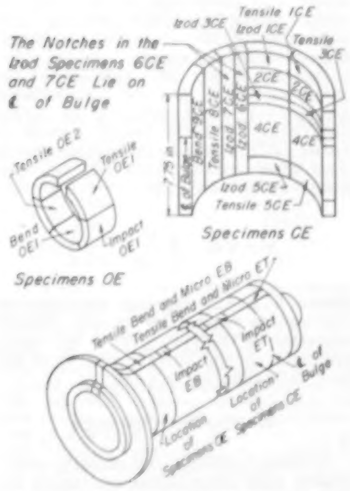


Fig. 47. Location of Specimens Listed in Table XVII and XVIII

Figure 40 shows the amount of taper required when punching relatively deep holes. The length of the taper determines the amount of draft required to allow the punch to be withdrawn from the forging.

In addition to various types of symmetrical forgings shown, some unsymmetrical parts are readily forged. These include bolts of many sizes and designs, rod ends, trunnion forgings, steering sectors, universal joints, and a number of other parts with ends that have various shapes.

Design of Hot Extrusion Forgings

Hot extrusion is used for making regular or irregular cup-shaped parts. The two principal types of hot extrusions are called straight extrusion, in which the metal is unconfined as in Fig. 42, and controlled extrusion where the metal is confined as in Fig. 43. More draft is allowed in a controlled extrusion because the flow of metal is restrained, and more stock is allowed because a flash is formed.

The limitations of size for a range of small hot extrusions are shown in Table XIV. Tables XV and XVI list the recommended dimensional tolerances applicable to straight extrusions and controlled extrusions, respectively. The tolerances in Table XV refer to the dimensions shown in Fig. 44 and the tolerances given in Table XVI refer to the dimensions shown in Fig. 45.

Mismatch Tolerances for a 0.2 to 0.8-lb forging are 0.008 in.; 1.0 to 4.0-lb, 0.010 to 0.012 in.; 10-lb, 0.016 in.; 20-lb, 0.022 in. and 30-lb, 0.026 in. Mismatch is defined in Fig. 46. Mismatch tolerance must be added to other tolerances.

Machining Allowance for forgings up to 20 ft long, up to 12 in. OD and 5 in. ID are ½ in. on length, 5/32 in. on the OD and ⅛ in. on the ID.

Mechanical Properties are dealt with in Tables XVII and XVIII and Fig. 47. A part of the extrusion was die-forged and then extruded in the barrel section. In the area where the effect of the extrusion operation began at the end of the die-forged or hammered area, the flow lines were very irregular and curved or bulged to the outside surface.

The extrusion was approximately of 8-in. diam, 4 ft long, and with ¾-in. wall thickness.

In straight extrusion there is no flash line; thus, transverse flash-line tests could not be made.

Table XVII. Mechanical Properties of a Hot Extrusion at Various Locations and Orientations (4340 Steel)

Code	Location	Orientation	Yield Strength, psi	Tensile Strength, psi	Gage Length,[a] in.	Elongation, %	Reduction of Area, %
EB	Open end	Longitudinal	178,500	189,500	2	14.5	46.7
OE1-1	Open end	Transverse	173,500	188,200	1	12.5	37.8
OE1-2	Open end	Transverse	171,000	189,500	1	10.0	38.3
OE1-3	Open end	Transverse	174,700	189,500	1	14.0	38.0
OE2-1	Open end	Transverse	175,500	191,500	1	12.0	38.5
OE2-2	Open end	Transverse	175,500	190,200	1	12.5	37.8
OE2-3	Open end	Transverse	173,500	188,300	1	12.0	40.3
ET	Closed end (at bulge)	Longitudinal	176,500	189,500	2	14.0	47.0
8CE	Closed end (at bulge)	Longitudinal	180,000	190,000	2	14.0	47.5
3CE	Closed end (at bulge)	Transverse	176,170	188,600	1	13.0	36.7
1CE	Closed end	Transverse	184,970	189,530	1	11.0	19.0
5CE	Closed end	Transverse	176,900	189,380	1	12.5	34.7

(a) Specimens with 2-in. gage length were standard 0.505-in. diam. Specimens with 1-in. gage length were subsize 0.250-in. diam.

Table XVIII. Izod Impact and Bend Properties of a Hot Steel Extrusion at Various Locations and Orientations

Code	Location	Orientation	Izod Impact, ft-lb	Bend Angle, deg
EB	Open end	Longitudinal	22, 22	70
OE	Open end	Transverse	16.5, 15, 17, 16.5	36, 37, 37, 37
ET	Closed end	Longitudinal	22, 22	74
6CE	Closed end (bulge)	Longitudinal	24	....
7CE-9CE	Closed end (bulge)	Longitudinal	24.5	90
3CE	Closed end (bulge)	Transverse	19.5	....
1CE	Closed end	Transverse	16.0	....
5CE	Closed end	Transverse	15.0	....

Helical Steel Springs

By the ASM Committee on Springs

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THIS ARTICLE deals with extension and compression springs, both cold wound and hot wound. The proper selection of spring steel wire and the principal considerations of spring design are emphasized.

Stress Computations

Charts that recommend categorically a design stress for a given spring steel can be a reliable guide for springs used in static service only, unless otherwise qualified. Charts of any sort are of value only when it is known whether the data are for springs with or without presetting, whether the cited nominal stresses have been increased by a "correction factor" or a "safety factor", and to what wire size they apply.

The spring design formulas given in Table I are valid for extension and compression springs below the stress at which yielding begins. Much of the labor of computation in design can be eliminated by the use of "spring slide rules".

When a helical spring is deflected by axial loading, the wire is in torsion or a combination of torsion and bending. In a straight torsion bar spring of circular section, twisting produces a shear stress uniform at every point on the surface, but in a helical spring coiled from round wire the stress at the inside of the coil is higher. A failure at some other point usually is caused by a flaw in the surface of the wire. This nonuniformity of shear stress is evaluated by the Wahl correction factor, K.

The correction of nominal stress is small for springs of index, D/d, greater than 12, as shown in Fig. 1. Statically loaded springs that are not preset, and must not take a permanent set should be computed with the correction factor only if the stresses are near maximum for the steel and if the spring index is low. The correction should always be made for springs subjected to fatigue loading.

Compression Springs

The usual types of ends for compression springs are shown in Fig. 2, in order of increasing cost from (*a*) to (*d*). In addition, the cost of grinding increases with close tolerances on squareness and length.

When springs are designed to work at maximum stresses, allowance should be made for the effect of the specified type of end on the spring stresses. For example, in a compression spring with squared, or squared and ground, ends the number of active coils will not remain constant throughout the entire deflection of the spring, and this results in spring loading rate and spring stress different from those originally calculated. This is especially important in springs having less than 10 coils, as changes in the number of active coils result in high percentage changes in stress. The number of active coils changes because part of the active coil adjacent to the squared end closes down solid and becomes inactive as the spring approaches the fully compressed condition. In designs where this is objectionable, loads at two positions of compressed length should be specified on the manufacturing print in order to assure load rates and stress levels no higher than those calculated. The control of load in this way also controls the number of active coils and therefore the spring stress over the deflection range. If, in addition, close tolerances are specified on other dimensions, manufacturing costs will increase.

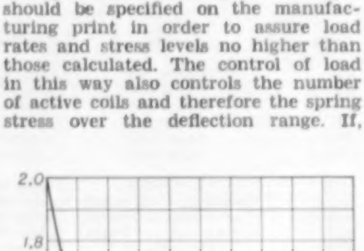


Fig. 1. Values of the Wahl Correction Factor. Spring index is diameter of spring, D, divided by diameter of wire, d.

Supplements the article on pages 644 to 647 of the 1948 ASM Metals Handbook

In springs working at high stresses, tolerances that do not increase calculated stresses should be liberal so that tolerances on other dimensions that might increase spring stresses may be held closely. Thus, if the number of coils must be held closely in order to keep spring stresses in control, tolerance on free length with ends ground should be large.

Active Coils. The number of active coils equals the total number of coils less those that are inactive at each end. For plain ends ground, the number of inactive coils depends on wire diameter and pitch of the spring. The number of active coils in a spring with plain, unclosed ends ground would approximately equal the number of turns of the wire untouched by grinding. One inactive coil on each end should be allowed in springs with squared ends, or squared ends ground. For springs of less than five coils, this rule should be applied with care; in some springs, the degree of squareness should be considered.

Solid Heights for types of ends (*a*) and (*b*) in Fig. 2 are computed by multiplying the wire diameter by the total number of coils plus one. Solid height of type (*c*) equals wire diameter times total number of coils plus 0.75. In type (*d*) the solid height is equal to the wire diameter times the total number of coils. A spring should be designed so that the coils do not touch or clash, since this will induce wear, fretting corrosion and failure. The maximum solid height, specified primarily for inspection, should be determined after consideration of clearances and tolerances on wire size, to allow spring manufacturers to meet economically the requirements established for solid height.

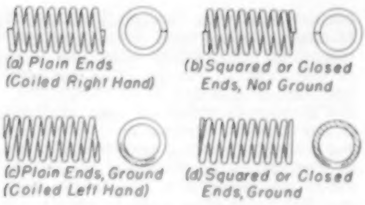
Because square wire enlarges at the inner surface of the coil and becomes trapezoidal during coiling of the spring, calculation of solid height should be based on the maximum section thickness after coiling. This can be computed by the formula

$$h_1 = 0.48\ h\left(\frac{OD}{D} + 1\right)$$

where h is the original thickness of the square wire, OD is the outside diameter of the spring, D is the mean diameter of the spring, and h_1 is the new thickness after coiling.

Extension Springs

Extension springs are usually close-wound with some initial tension at the discretion of the springmaker unless specified with definite space between


(a) Plain Ends (Coiled Right Hand)

(b) Squared or Closed Ends, Not Ground

(c) Plain Ends, Ground (Coiled Left Hand)

(d) Squared or Closed Ends, Ground

Fig. 2. Types of Ends for Compression Springs. Cost increases from (a) to (d).

coils, or close-wound with no initial tension (difficult to accomplish), or close-wound with a definite initial tension, usually within ±15%. In making stress calculations, initial tension is included in the load *P*, and if *P* is measured on a spring balance, initial tension is included in the measurement obtained. The lower curve in Fig. 3 shows the minimum stress for initial tension when added manufacturing charges for this operation are to be minimized or avoided. The other two curves show maximum stresses for hard drawn wire and for oil-tempered wire.

The necessity for fastening extension springs to some other part may require secondary operations or a costly fastening design. End hooks with sharp bends may have stress concentrations that increase computed stresses in the spring by a factor of 2 or 3.

End Hooks. A general approach to the selection of economical ends is shown in Fig. 4, in which 20 types of ends have been ranked from *A* to *F* in order of increasing cost.

Stresses in end hooks are a combination of torsion and bending. Tensile stresses diminish toward the body of the spring, where torsional stresses prevail. There is a region where they superimpose and are difficult to compute accurately. If the last coil of the spring adjacent to the end hook is reduced in diameter, the stress in the last coil and the end hook will usually be less than in the other coils.

Table I. Design Formulas for Helical Extension and Compression Springs

Round Wire	Square Wire
Stress for Statically Loaded Springs, psi	
$S = \frac{2.55\,PD}{d^3}$	$\frac{2.4\,PD}{h^3}$
$S = \frac{FGd}{\pi D^2N}$	$\frac{FGh}{2.32\,D^2N}$
Stress Corrected by the Wahl Factor (Fig. 1), psi	
$S_K = \frac{2.55\,PD}{d^3}\left[\frac{4C-1}{4C-4}+\frac{0.615}{C}\right]$	
Wire Size for Given Load and Stress, in.	
$d^3 = \frac{2.55\,PD}{S}$	$h^3 = \frac{2.4\,PD}{S}$
Deflection of the Spring Under Load, in.	
$F = \frac{8\,PD^3N}{Gd^4}$	$\frac{5.58\,PD^3N}{Gh^4}$
Spring Loading at a Given Deflection, lb	
$P = \frac{FGd^4}{8\,D^3N}$	$\frac{FGh^4}{5.58\,D^3N}$
$P = \frac{Sd^3}{2.55\,D}$	$\frac{Sh^3}{2.4\,D}$

S is nominal shear stress, in pounds per square inch; *P* is spring load or force, in pounds; *D* is mean diameter of the spring, in inches (outside diameter of the spring minus the wire diameter); *d* is diameter of the wire, in inches; *h* is the size of the square wire before coiling, in inches; *F* is the deflection, in inches, under load *P*; *G* is the modulus of elasticity in shear (modulus of rigidity), equal to 11.5 million psi for ordinary steels and 10 million psi for stainless steel near room temperature; *N* is the number of active coils; *C* is the spring index, *D/d*; and *K* is the Wahl correction factor.

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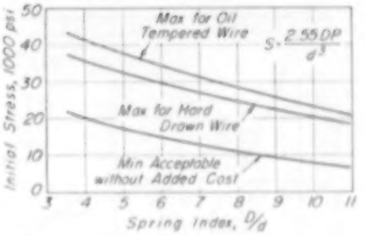

Fig. 3. Shear Stress of Initial Tension (Not Wahl-Corrected)

The bending stresses in the end hook may be calculated from the equation:

$$S_b = \frac{32\,PR}{\pi d^3}\left(\frac{r_c}{r_i}\right)$$

where *PR* is the bending moment (load times moment arm from centerline of load application to centerline of wire), r_c is the radius of the sharp bend measured to centerline of wire and r_i is the inside radius of the sharp bend. The ratio r_c/r_i is an approximate evaluation of the stress-concentrating effect of the conformation these radii describe. The ratio indicates the destructive effect of a small radius r_i. The smaller this radius, the higher the stress at the corner, other values being the same.

Because of the possibilities for overextension and the stress concentration in the ends, allowable stresses are more likely to be exceeded in extension springs than in compression springs. Therefore, allowable stresses 20% less than for compression springs are sometimes recommended for extension springs. However, when stresses in the ends are accurately known and the stroke of the spring is controlled in design of the spring or the external parts, the same values for allowable stresses can be used for extension springs as for compression springs that have not been preset.

Cold Wound Springs

Cold wound springs include most small extension and compression springs and are usually made of cold

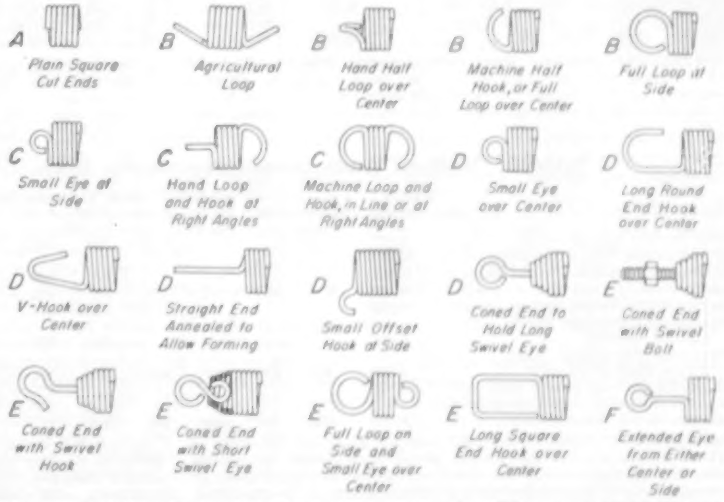
A
Plain Square Cut Ends
B
Agricultural Loop
B
Hand Half Loop over Center
B
Machine Half Hook, or Full Loop over Center
B
Full Loop at Side
C
Small Eye at Side
C
Hand Loop and Hook at Right Angles
C
Machine Loop and Hook, in Line or at Right Angles
D
Small Eye over Center
D
Long Round End Hook over Center
D
V-Hook over Center
D
Straight End Annealed to Allow Forming
D
Small Offset Hook at Side
D
Coned End to Hold Long Swivel Eye
E
Coned End with Swivel Bolt
E
Coned End with Swivel Hook
E
Coned End with Short Swivel Eye
E
Full Loop on Side and Small Eye over Center
E
Long Square End Hook over Center
F
Extended Eye from Either Center or Side

Fig. 4. Relative Cost of Various End Hooks for Extension Springs. Cost increases from A to F.

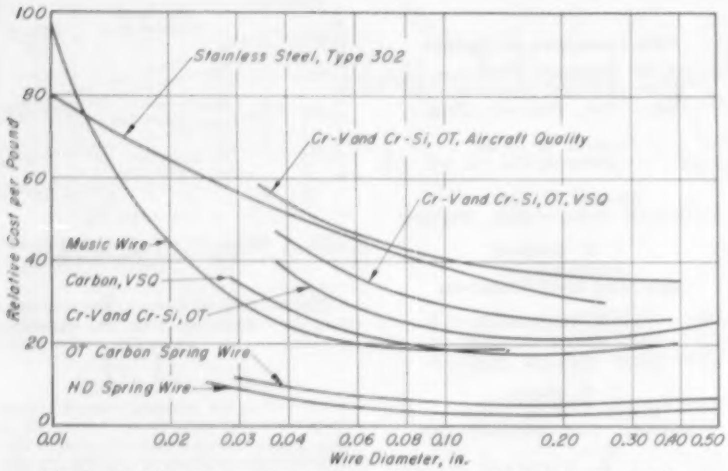

Fig. 5. Relative Cost of Spring Wires. VSQ means valve spring quality.

drawn or pretempered wire of less than ⅝-in. diam. A small number of springs are cold wound from annealed wire, hardened and then tempered after being formed.

Types of Wire. Steels for cold wound springs differ from other constructional steels chiefly in the degree of cold work, the higher carbon content, the fact that they can be furnished in pretempered condition (all of which increases strength), and in higher surface quality, which improves fatigue properties. The principal types are listed in Table II.

The grade known as "hard drawn spring wire" is the least costly spring wire. It is of comparatively low quality and not guaranteed to be free from surface imperfections such as hairline seams. This wire, in the hard drawn condition and not tempered, is used ordinarily for applications involving low stresses or static conditions.

Oil-tempered wire, a general-purpose wire, less resistant to the effects of plating than hard drawn spring wire, obtains its spring properties from heat treatment. It is slightly more expensive than hard drawn wire, and superior in surface quality and fatigue.

Music wire is the highest quality carbon steel wire for small springs. It is subject to the least damage by electroplating and, along with the wires of valve spring quality, is of the highest surface quality.

These three types of wire are used in the greatest number of applications. For instance, among cold wound automotive spring applications, about 35% are oil-tempered wire, 35% music wire, and 25% hard drawn spring wire.

Carbon steel wire of valve spring quality is the least costly of the valve spring wires, all of which have high surface quality. Chromium-vanadium steel wire of valve spring quality is superior to carbon steel wire of the same quality for service at 250 F and above. Springs of chromium-silicon steel wire can be used at temperatures as high as 450 F.

Type 302 stainless steel, cold drawn, has high surface quality and heat resistance, as well as the best corrosion resistance of all the steels in Table II. However, type 316 is superior, particularly for resistance to pitting in salt water. Stainless steel springs are not interchangeable with other steel springs without making accompanying design changes so as to compensate for the difference in the modulus of rigidity, G.

Carbon steel wire of valve spring quality and chromium-vanadium steel wires of both spring and valve spring quality can be purchased in the soft annealed condition to permit severe forming involved in springs of small spring index and sharp bends in end hooks, and can be quenched and tempered to spring hardness after forming. However, without expensive control of processing, such springs will have wider

Table II. Steels for Cold Wound Springs

Trade Designation	ASTM Designation	C	Mn	Si	Cr	V or Ni	Usual Sizes, in. diam
Hard Drawn Spring Wire	A 227	0.45 to 0.75	0.60 to 1.20	0.10 to 0.30	....	....	0.028 to 0.500
Oil Tempered Wire, Composition A	A 229	0.55 to 0.75	0.80 to 1.20	0.10 to 0.30	....	....	0.220 to 0.625
Oil Tempered Wire, Composition B	A 229	0.55 to 0.75	0.60 to 0.90	0.10 to 0.30	....	....	0.020 to 0.218
Music Wire	A 228	0.70 to 1.00	0.20 to 0.60	0.12 to 0.30	....	....	0.007 to 0.250
Carbon Steel, Valve Spring Quality	A 230	0.60 to 0.70	0.50 to 0.80	0.12 to 0.30	....	....	0.080 to 0.375
Chromium-Vanadium Steel, Spring Quality	A 231	0.45 to 0.55	0.60 to 0.90	0.15 to 0.30	0.80 to 1.10	0.15 min V	0.028 to 0.375
Chromium-Vanadium Steel, Valve Spring Quality	A 232	0.45 to 0.55	0.60 to 0.90	0.12 to 0.30	0.80 to 1.10	0.15 to 0.25 V	0.032 to 0.437
Silicon-Manganese Steel, SAE 9260	A 59	0.55 to 0.65	0.70 to 1.00	1.80 to 2.20	....	....	0.035 to 0.375
Chromium-Silicon Steel, SAE 9254	...	0.50 to 0.60	0.50 to 0.80	1.20 to 1.60	0.50 to 0.80	....	0.035 to 0.375
Stainless Steel, Type 302	A 313	0.15 max	2.00 max	1.00 max	18.0 to 20.0	8.0 to 9.5 Ni	0.006 to 0.469

USUAL CONDITION: Hard drawn spring wire, music wire and stainless steel are cold drawn; the larger sizes of stainless steel may be cold rolled. Oil tempered wire (compositions A and B), carbon steel of valve spring quality, chromium-vanadium steel of valve spring quality, silicon-manganese steel, and chromium-silicon steel are quenched and tempered. Chromium-vanadium steel of spring quality is annealed, then cold drawn a small amount, quenched and tempered.

Table III. Minimum Tensile Strength Specifications of Steels for Cold Wound Springs(a)

Trade Designation	ASTM Designation	Minimum Tensile Strength for Diameters (in.) Listed, 1000 psi												
		0.004	0.009	0.016	0.022	0.032	0.035	0.063	0.091	0.135	0.177	0.250	0.312	0.375
Hard Drawn Spring Wire	A 227	....	....	....	271(b)	265	261	237	220(c)	206	195	182	174	167
Oil Tempered Wire, Composition A	A 229	....	....	....	....	....	....	....	....	....	....	180	178	175
Oil Tempered Wire, Composition B	A 229	....	....	....	....	275	268	242	225(c)	210	195	....	....	....
Music Wire	A 228	439	393	362	345	327	322(c)	293	276(c)	258	238(c)	220(c)	....	....
Carbon Steel, Valve Spring Quality	A 230	....	....	....	....	....	....	....	210(d)	205(e)	200(f)	195(g)	....	....
Chromium-Vanadium Steel, Spring Quality	A 231	....	....	....	....	285	275	265	255	245	235	230	225	....
Chromium-Vanadium Steel, Valve Spring Quality	A 232	295	295	295	295	295	292(c)	268(c)	220(c)	235	222(c)	209(c)	203(c)	199(c)
Silicon-Manganese Steel, SAE 9260	A 59	....	....	....	....	....	275(h)	265(h)	255(h)	250(h)	245(h)	240(h)	235(h)	230(h)
Chromium-Silicon Steel, SAE 9254	...	....	....	....	....	....	285(i)	275(i)	265(i)	255(i)	245(i)	235(i)	230(i)	225(i)
Stainless Steel, Type 302	A 313	325	325	308	296	277	273(c)	255(c)	240(c)	217(c)	195	175	160	140

(a) Applicable chemical compositions are given in Table II. It should be noted that the values given here relate to tensile strengths, not shear strengths, and therefore are not used directly as design values. (b) Applicable to 0.028-in. diam. (c) Interpolated value. (d) Applicable to 0.093 to 0.128-in. diam. (e) Applicable to 0.129 to 0.162-in. diam. (f) Applicable to 0.163 to 0.192-in. diam. (g) Applicable to 0.193 to 0.250-in. diam. (h) Representative minimums. The specification does not list values of minimum tensile strength. (i) The specification does not list values for minimum tensile strength. Acceptable values for regular temper of Rockwell C 47 to 51 are shown. For special temper of Rockwell C 50 to 54, values are 20,000 psi higher.

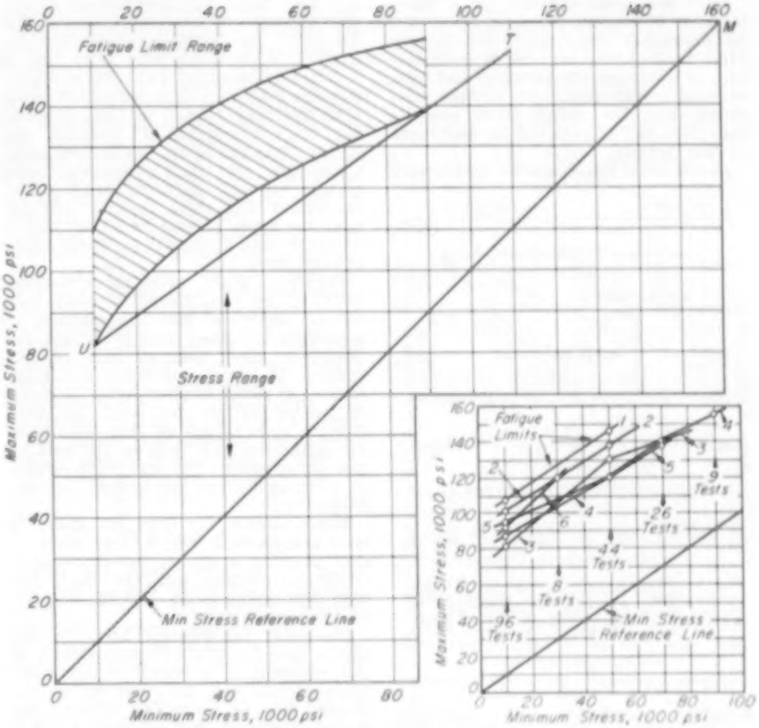

Fig. 6. Fatigue Limits for Music Wire Springs. Table IV gives conditions.

Table IV. Descriptions of Springs for Which Test Data Are Shown in Fig. 6

Spring No.	Wire Diam, in.	Spring OD, in.	Spring Index	Free Length	Total Turns	Active Turns	Total Number Tested
1	0.032	0.375	10.7	0.87	6.0	4.2	16
2	0.032	0.250	6.8	1.062	7.0	5.2	28
3	0.048	0.625	12.0	1.75	7.0	5.2	38
4	0.102	0.875	7.6	2.37	7.0	5.2	43
5	0.121	0.875	6.2	2.25	7.5	5.7	35
6	0.177	0.875	4.9	2.25	7.5	5.7	25

Data shown in Fig. 6 are average fatigue limits from S-N curves for 185 unpeened springs of various wire diameters run to 10 million cycles of stress. All stresses were corrected for curvature using the Wahl correction factor. The springs were automatically coiled, with one turn squared on each end, then baked at 500 F for 1 hr after which the ends were ground perpendicular to the spring axis. The test load was applied statically to each spring and a check made for set three times before fatigue testing. The springs were all tested in groups of 6 on the same fatigue testing machine at 10 cycles per second. After testing, the unbroken springs were again checked for set and recorded. Number 4 springs, tested at 155,000 psi max stress, had undergone about 2½% set after 10,000,000 stress cycles but the stresses were not recalculated to take this into account. None of the other springs showed appreciable set. The tensile strengths of the wires were according to ASTM A 228.

dimensional spread, greater hardness variations, and lower surface quality than will those of hard drawn or oil-tempered wire.

Springs made of music wire, oil-tempered wire or hard drawn wire should be heated in the range between 350 F and 750 F, but preferably at 500 F for 30 min or longer as soon as possible after coiling, to relieve stresses. Type 302 stainless steel springs should be heated at 750 to 800 F for 30 min or longer to relieve stresses resulting from the coiling operation.

Specifications. The steels shown in Table II exhibit much greater differences in fatigue performance than in performance in static applications. The similarity of composition of the first five steels shown emphasizes that performance differences depend on high surface quality rather than on differences in composition. Nor are the minimum tensile strengths notably different, as shown in Table III.

Specification requirements for these wires call for twist, coiling, fracture or reduction of area tests in addition to the minimum requirements for tensile strength. Surface requirements are specified in terms of visual examination. Sometimes this examination is made after an acid etch to remove 1% of the wire diameter.

Inspection. Magnetic particle inspection is the most reliable and practical nondestructive inspection method for springs that involve human safety or for other reasons must not fail because of surface defects. The inspection is always concentrated selectively on the inside of the coil, which is more highly stressed than the outside and the most frequent location of failure.

Freedom from surface defects is of paramount importance in some applications of highly stressed springs for shock and fatigue loading, especially where replacement of a broken spring would be difficult and much more costly than the spring itself.

Decarburization. Total loss of carbon from the surface during a heat treating process is infrequent in modern wire mill products. Partial decarburization of spring wire is often blamed for spring failures, but quench cracks and coiling-tool marks are more frequently the actual causes. In wires of valve spring or aircraft quality, a decarburized, ferritic ring around the wire circumference is a basis for rejection.

Cost of Spring Steels. The relative costs of various spring steels in the form of round wire are given in Fig. 5. The amount of material in a spring can be minimized by designing for the highest safe stress level. From the equation for volume of material,

$$V = \text{Spring Energy}\ (4G/S^2),$$

a reduction of 5% in stress level increases the volume of material 11%.

Cost of Springs. Tolerances are often the most important factor in spring cost, and should be selected with cost in mind. Tolerances superimposed on tolerances are especially costly. For example, if a free length tolerance were specified in addition to load tolerances at each of two deflections, the cost of manufacturing the spring could be much higher than if free length tolerance were unspecified. Important dimensions can sometimes be held at no additional cost by allowing wider tolerances elsewhere. The tolerance on spring diameter and pitch are the least expensive to hold.

Stress Range. In most spring applications the load varies between an initial and a final condition. For example, an automotive valve spring is compressed initially during assembly, and during operation it is compressed cyclically by an additional amount each time the valve opens.

The shear stress range (that is, the difference between the maximum and minimum stress of the cycle to which a helical steel spring may be subjected without fatigue failure) decreases gradually as the minimum and maximum stresses of the loading cycle increase. The allowable maximum stress increases up to the point where permanent set occurs. At this point, the maximum stress is limited by the occurrence of excessive set.

Figure 6 shows a fatigue diagram for music wire springs of the various wire diameters and indexes described in Table IV. In this diagram the 45-deg line OM represents the minimum stress of the cycle, while the plotted points represent the fatigue limits for the respective minimum stresses used. The vertical distances between these points and the minimum stress reference line represent the stress ranges for music wire springs.

In fatigue testing some scatter may be expected. The width of the band in Fig. 6 may be attributed partly to the normal differences in tensile strength of the wires with change in wire diameter. There appears to be a trend toward higher fatigue limits for the smaller wire sizes. Line *UT* is drawn so as to intersect line *OM* at the average ultimate shear strength of the wires.

Safe maximum stresses for a minimum of 10 million cycles of stress will be somewhat lower than the fatigue limit band chiefly because of such factors as tolerance variations in the wire, especially with regard to surface condition, and the spring itself and its manufacture, as referred to elsewhere in this article.

Commercial tolerances on spring wire will also affect the selection of allowable stress for a production spring. For instance, the 0.0005-in. tolerance on 0.032-in. diam music wire gives rise to a stress variation of 4½%. In addition, stresses may vary proportionately with load tolerance from 7 to 15%, depending on the number of coils in the spring. Tolerances on number of coils, squareness and spring diameter also permit stresses different from those calculated. For these reasons, stresses near the upper fatigue limits, as shown in Fig. 6, may be unsafe for some kinds of applications.

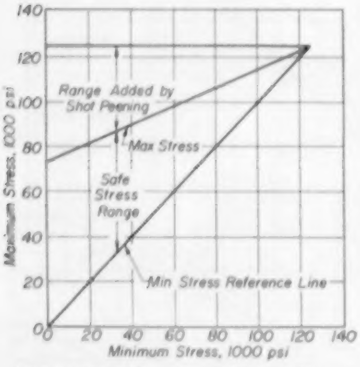

Fig. 7. Safe Ranges of Shear Stress (Corrected) for Springs Made from Valve Spring Quality Wires of Less than 0.207-In. Diam

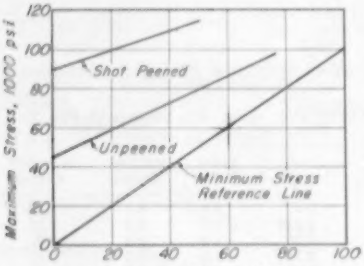

Fig. 8. Safe Ranges of Shear Stress for Type 302 Stainless Steel Springs Using Wahl Corrected Stresses for Peened and Unpeened Springs.

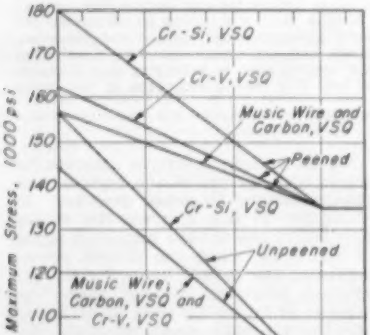

Fig. 9. S-N Diagrams for Peened and Unpeened Springs of Spring Index, D/d, Less than 10 and with Minimum Working Stress 20,000 Psi (Stresses Computed with Bending). All wires of high surface quality

Figure 7, which gives recommended stress ranges that include a safety factor for individual spring variations, is applicable to carbon steel or chromium-vanadium steel, both of valve spring quality. In using this chart for valve springs or other springs likely to surge or vibrate within the coils, the wire size for a given spring rate should be the minimum that falls in the area of safe stress range. This condition results in a spring having the highest natural frequency.

Stress ranges for type 302 stainless steel are given in Fig. 8. The effect of shot peening is shown, but allowances from the average must be made for wire size, spring index, and the absence of presetting.

Designing for Definite Life. To design a spring for infinite life when it is not required is a waste of material. Such springs can be designed to the desired life by using an appropriate fatigue curve or S-N diagram to give an approximation of allowable stresses. Fig. 9 shows S-N diagrams for springs made from several types of wire having high surface quality. Grades of steel in which seams or scratches up to 4% of the diameter or 0.010 in. deep are permitted cannot be selected on the basis of S-N data because the effects of such defects on spring life are too variable. Such wires should be used only for static applications or for springs that are designed for less than 10,000 load applications.

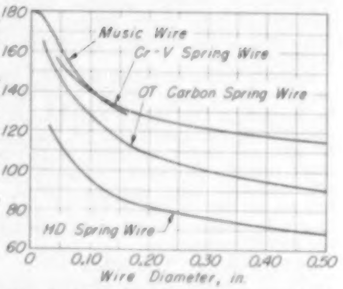

Fig. 10. Limiting Shear Stresses for Unpeened, Not Preset Compression Springs for Less than 10,000 Applications of Load. Original test data were 10% higher.

The data of Fig. 9 show, for various cycles to failure, the approximate allowable stress above which the probability of failure increases rapidly. Although a reliable selection of allowable stress can generally be determined from this diagram, the optimum stress can be determined only by testing sample springs that have been fabricated by the actual sequence of operations employed in full-scale production.

Static Loading. The values in Fig. 10 can be used as uncorrected stress for

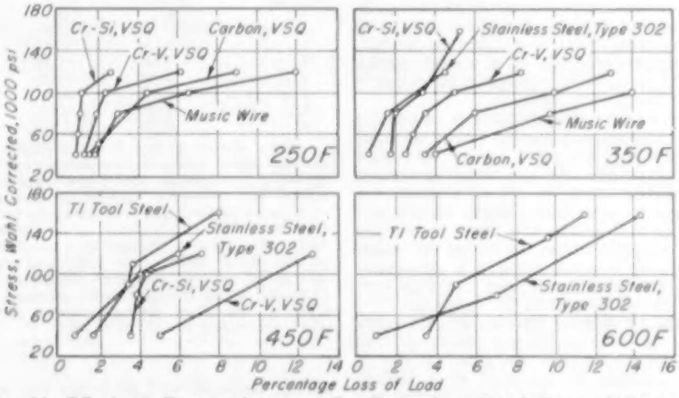

Fig. 11. Effect of Temperature on the Percentage Load Loss of Springs. Based on tests of thousands of springs. The steels are: (ASTM) A228, music wire; A230, carbon steel, valve spring quality; A232, chromium-vanadium steel, valve spring quality; A313, type 302 stainless steel; 9254, chromium-silicon steel, valve spring quality; T1, high speed tool steel. All stresses Wahl-corrected. All springs were stress relieved after coiling, none were shot peened and all were at the indicated temperatures at least 72 hr.

Table V. Performance of Highly Stressed, Shock-Loaded Music Wire Springs

Max Stress,[a] 1000 psi	Stress Range,[a] 1000 psi	Wire Diam, in.	Spring Index, *D/d*	Cycles to Excessive Set
160	125	0.090[b]	3.9	2000
140	100	0.096	6.8	4000
157	101	0.037[c]	3.4	5000
161	115	0.148	6.3	4000
163	83	0.053	6.6	6000
170	87	0.038	6.5	6000
137	81	0.062[b]	4.8	7500
132	89	0.055	5.1	5000

(a) Uncorrected. (b) Seven-strand wire. (c) Three-strand wire.

static loading of unpeened springs and for designs involving less than 10,000 load applications. For extension springs having adverse end-hook bends, the values should be reduced by 20%.

Most compression springs are preset to permit use at higher stress. Compression springs can be made to close solid without permanent set, and without presetting, if the shear stress in the fully compressed spring is less than about 45% of the tensile strength of the wire. The maximum shear stress obtainable in a fully compressed spring that has been preset is about 33% higher, or approximately 60% of the tensile strength of the wire. Presetting will save 40% of the steel otherwise required. This saving is usually more than the cost of presetting for wire of more than ⅛-in. diam. A second advantage is that less space is required for the spring. However, presetting is not recommended for springs required to hold a definite load within narrow tolerances for a long period of time.

Ordnance springs are typical of many long-stroke springs having limited space requirements in addition to limited life requirements and subjected to shock loading. Stranded wire springs have sometimes been used because of their inherent damping and the accompanying availability of either higher spring forces at the same stress levels, or lower stresses at the same loads. However, stranded wire springs have the serious disadvantages of high cost and chafing between coils. Stress level, stress range and "life" (until set becomes excessive) of some springs used at high stresses, including some stranded wire springs, are listed in Table V. The "life" of these springs is not entirely dependent on maximum operating stress and stress range but is also affected by the shock-loading cycle that is exerted by the ordnance application.

Shot Peening of springs improves fatigue strength by prestressing the surface in compression and can be applied to wire of 1/16-in. diam and more. It is effective on surfaces with shallow defects. The effect of shot peening may be noted in Fig. 7, 8 and 9. In both compression and extension springs, the important surface to be blasted is the inside of the spring. The kind of shot used is less important than other factors, such as the duration of peening. The effect of shot peening is removed at temperatures above 500 F. For further information on shot peening, the reader may refer to the article on page 104 of the 1954 Supplement to the Metals Handbook.

Heat Resistance. Tests of thousands of springs under various loads at elevated temperatures are summarized in Fig. 11. Plain carbon spring steels of valve spring quality are reliable at stresses up to 80,000 psi (corrected) at temperatures no higher than 350 F, in wire sizes not greater than ⅜ in. Slightly more severe applications may be successful if springs are preset at the operating temperature with loads greater than those of the application. Plain carbon spring steels of valve spring quality should not be used at temperatures above 400 F.

Except for high speed steel, these tests revealed no advantage in springs heat treated after coiling compared with those at the same hardness values made of pretempered wire and properly stress relieved.

Electroplating can cause hydrogen embrittlement of springs. Hence, baking for 1 to 3 hr at 350 to 400 F is recommended immediately after plating, and before any flexing, to remove hydrogen.

For further discussion of the alleviation of effects of hydrogen in springs, the reader may refer to page 100, in the article on coatings in this Supplement.

Hot Wound Springs

Most hot wound springs are made from carbon steel in the hot rolled condition; for some applications bars are centerless ground before coiling. The usual size of wire or bar is ⅜ to 3-in. diam. Steels 1090 and 1095 are the most widely used.

A typical compression spring is wound to a free height in excess of the specified final dimension, hardened, tempered, and compressed solid several times to preset the spring to the final free height specified. Presetting leaves residual stresses opposite to the direction of service stresses at the position of maximum stress. Therefore, when a load is applied to a preset spring, it first reduces this negative residual stress to zero before positive stresses are developed. Thus, the useful range of stress is increased.

Steels. In the railroad industry, 1095 steel is used almost exclusively for freight car suspension and draft gear springs. The 5100, 8600 and 9200 grades of alloy steel predominate in passenger car and locomotive suspensions. For earthmoving and general industrial applications, the most common alloy grades, in the order of usage, are 5100 (because of cost), 51B00, 8600, 9200, 6100 and, recently, 4100 for bars of more than 2-in. diam. In the automotive industry, centerless ground, and sometimes precision rolled, alloy steel is in extensive use.

Selection of Steel. Hardenability bands are used as a basis for alloy steel selection, with a criterion of Rockwell C 50 minimum center hardness in the as-quenched bar. (The reader may refer to the article "Selection of Constructional Steel", pages 1 to 20, 1954 Supplement to Metals Handbook, for recommended procedures in selecting steel on the basis of hardenability.)

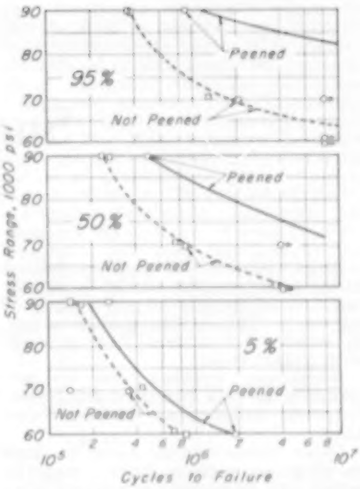

Fig. 12. Probability of Failure of Hot Wound Springs Made from 5/8 to 1 1/16-In. Diam 8650 and 8660 Hot Rolled Steel and Heat Treated to between 429 and 449 Bhn. Shot peening was to an average arc height of 0.008 in. on the type C Almen strip at 90% visual coverage. The upper graph shows 95% probability of failure, the middle graph 50% and the lower graph 5%.

Fatigue. Stress range is of much greater importance than mean stress in determining the fatigue life of hot wound springs. Many fatigue data have been accumulated that concern large hot wound springs made from bars with commercial hot rolled surfaces. Probably because of surface defects, the scatter of results is wide and interpretation is difficult. Typical results are given in Fig. 12.

The effect of seam location, as determined by magnetic particle inspection, has been evaluated by comparing seamed springs with control springs having no seams: Springs with seams at the inside diameter of the spring had 46% of normal life; those with seams at the mean diameter, 57% of normal life; and with seams at the outside diameter, 84% of normal life. These results may vary with the D/d ratio. Springs with large index will be more sensitive to defects on the outside diameter.

Decarburization is detrimental since it increases the tendency of the spring to take a permanent set.

Heat Treatment. Temperature ranges for coiling, quenching and tempering are given in Table VI. Springs may be quenched directly from the coiling operation or coiled at the temperature shown, allowing the spring to cool in air until it becomes distinctly black, and then to reheat in a suitable furnace for hardening. Hot wound springs may be quenched individually in fixtures in agitated oil at 110 to 140 F, removed when the surface is at 250 to 400 F, and tempered immediately.

Table VI. Temperature Ranges for Forming, Quenching and Tempering of Hot Wound Springs

Steel	Temperature for Forming, deg Fahr	Quenching Temperature,(a) deg Fahr	Tempering Temperature, deg Fahr	Hardness Range, Bhn
1085	1600 to 1800	1600 to 1650	750 to 850	444 to 388
1095	1600 to 1800	1600 to 1650	750 to 850	444 to 388
9260	1600 to 1800	1600 to 1650	800 to 925	514 to 415
9262	1600 to 1800	1600 to 1650	825 to 925	477 to 415
5150	1600 to 1650	1500 to 1550	775 to 825	461 to 415
5160	1600 to 1650	1500 to 1550	775 to 875	461 to 415
51B60	1650 to 1800	1500 to 1550	775 to 850	461 to 415
6150	1600 to 1800	1600 to 1650	800 to 925	477 to 415
8650	1600 to 1650	1500 to 1550	775 to 825	461 to 415
8660	1650 to 1800	1500 to 1550	800 to 875	461 to 415
4150	1600 to 1650	1500 to 1550	775 to 825	461 to 415

(a) Quench in oil at 110 to 140 F.

Surface Finish of Metals

By the ASM Committee on Surface Finish

Subdivisions

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SURFACE FINISH may be defined as the deviation from an ideally smooth condition of the exterior or boundary of an object. This deviation is measured in terms of roughness and waviness with respect to lay.

Roughness, waviness and lay are classified in ASA Standard B46.1-1955, "Surface Roughness, Waviness and Lay".

Other characteristics could be used to evaluate surface finish, such as reflectivity, percentage of contact with a mating surface under controlled pressure, friction against another specified material, ability to generate noise or vibration in some specific application, or resistance to indentation for a given hardness and pressure.

Roughness is the relatively finely spaced deviations or irregularities that establish the predominant surface pattern. Although the ASA standard states that roughness height is to be rated in micro-inches (millionths of an inch) arithmetic average deviation from the mean surface, some instruments still measure the root-mean-square (rms) average deviation from the mean surface. This method of expressing surface roughness appears occasionally in technical publications. The rms average is about 10% greater than the arithmetic average.

Waviness is the irregularities of greater spacing than roughness. The ASA standard recommends that waviness height be rated in inches peak-to-valley distance, but much use is made of measurements in micro-inches average departure from the mean surface.

Lay is the direction of the predominant surface pattern.

Roughness and waviness readings are usually taken in a direction which gives the maximum reading. This is normally across the lay. The maximum width of surface irregularities to be included in a measurement of roughness height is specified as the roughness width cutoff. The closely spaced irregularities measured as surface roughness are generally visible to the eye. The more widely spaced irregularities, waviness, are not easily detected visually and may be of either greater or smaller magnitude than roughness.

When the lay of a surface has a pronounced direction, as is generally true for finishes produced by some form of machine tool, it is important to know the direction with respect to the lay in which the surface finish measurements are taken. It is important, too, in some applications, to have the lay in a certain direction.

Symbols and Conventions

Symbols and conventions that have been accepted generally for the description and specification of surface finishes are presented in the ASA standard. The symbol used to designate surface finish is the check mark with a horizontal extension, as shown in Fig. 1. Roughness, which is the more common surface parameter, is specified by inserting the height rating at the left of the long leg. If there is a maximum and minimum rating, the two numbers are inserted, one above the other. If a waviness specification is to be used, the maximum height rating is placed above the extension on the symbol. The designation for lay is placed under the extension and defines the direction relative to the normal surface as follows:

= Parallel to the boundary
⊥ Perpendicular to the boundary line
X Angular in both directions to the boundary line
M Multi-directional
C Approximately circular relative to center of the nominal surface
R Approximately radial relative to the center of the nominal surface.

Provision is also made in the symbol for stating widths of roughness and waviness, and the roughness width cutoff, which is the maximum width (in inches) of surface irregularities to be included in the measurement indicated. Often only the roughness height will be specified, but the symbol is flexible enough to allow specifying other surface characteristics when necessary.

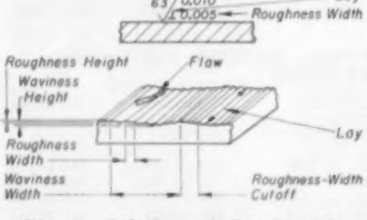

Fig. 1. Relation of Specification Symbols to Characteristics of Surface Finish

This is a new subject for the ASM Metals Handbook

An effort has been made to obtain some conformity in the surface finish ratings that are specified, rather than have these selected at random. A series of values recommended by the ASA standard are listed in Table I.

Instruments

Most of the instruments available for measuring surface finish employ electrical amplification of the motion of a stylus tracer. A block diagram of the arrangement of an instrument of this sort is shown in Fig. 2. There are a number of different instruments available with slightly varying characteristics, some indicating only, and some recording. Since most surfaces are complex and contain irregularities over a wide range of sizes, the slightly different instrument characteristics sometimes influence a numerical evaluation of surface roughness to some extent.

The particular type of instrument to be used depends largely on the information desired from the measurement. For production purposes, or an evaluation based on magnitude only, indicating instruments are generally satisfactory. To determine such characteristics as spacing of irregularities and shape of the profile, graphic records are necessary.

Most of the instruments for measuring surface roughness support the tracer on skids which bear directly on the surface being measured. Since the radius of the skids is large in comparison with the width of the irregularities measured as roughness, there is virtually no vertical displacement of the skids, whereas the stylus follows the deviation of the surface roughness from the mean condition. The vertical movement of the stylus generates a signal that is amplified and indicated or recorded as the surface roughness.

There should be no relative displacement caused by dirt or vibration between the tracer skids and the surface being measured. Variations in tracing speed produce variations in the roughness width cutoff and may result in erroneous measurements. Tracers may be traversed by hand but a suitable mechanical drive is recommended, since it assures more uniform velocity of motion. To assure the over-all accuracy of the instrument, it should be checked against known reference specimens, preferably having a surface roughness of the same order of magnitude as that of the work.

The closest spacing of irregularities that will be included in the measurement made by an instrument is determined primarily by the sharpness of the stylus used to trace a surface profile. However, if a stylus is sharp enough to detect extremely closely spaced irregularities, it will be fragile and will wear rapidly. A stylus radius of 500 micro-in. is conventional for most measurement, although other radii may be selected.

The ASA standard recommends that radii be chosen from the series 100, 500, 5000, 50,000, and so on, micro-in. The smaller stylus radii are used where it is desirable to know something of the effect of the more closely spaced irregularities. Larger radii are satisfactory where only the more widely spaced irregularities are important.

The maximum width of irregularities that will be measured may be determined by the low-frequency characteristics of the electrical circuits or the speed of tracing, and the reference plane provided, from which the deviations are measured. The use of skids resting on the surface being measured is satisfactory for irregularities in the range of surface roughness. For more widely spaced irregularities included in a waviness measurement, it is usually necessary to provide a separate reference plane for the tracer.

When measuring relatively soft materials, some consideration must be given to the pressure of the stylus on the surface; if the unit pressure is sufficient to indent the material, erroneous readings will be obtained.

Most instruments limit the maximum width of irregularities that will be measured (roughness width cutoff) to 0.030 in. Irregularities spaced more than 0.030 in. apart will not contribute to the measurement at all, or their effect will be attenuated. The ASA standard gives preference to the 0.030-in. roughness width cutoff, but values of 0.003, 0.010, 0.100, 0.300 and 1.000 in. are also mentioned and used.

An example of the use of a roughness width cutoff closer than 0.030 in. might be the measurement of surface roughness as an aid in controlling fatigue resistance of a surface subjected to variable tensile stresses. With metals that are especially sensitive to scratches, the closely spaced irregularities may provide the principal contribution to any increase of stress gradient causing fatigue failure, and if so it would be desirable to use 0.003-in. cutoff.

If two extensive surfaces must mate together, a measurement of roughness, or perhaps waviness, should be made with a longer width of cutoff to insure contact of a larger number of points on the two surfaces.

Although it is preferable to determine surface roughness by means of an instrument, this is not always feasible. Roughness comparison specimens can be used to evaluate approximate surface roughness having the characteristics of typical machined surfaces. It is important that the roughness comparison specimen have an appearance similar to the surface being evaluated. The ASA standard describes such specimens and gives the following values of preferred roughness height: 2, 4, 8, 16, 32, 63, 125, 250, 500 micro-in.

Precision reference specimens for checking the accuracy of measuring instruments are also described in the ASA standard. The normal surface profile of these consists of a series of isosceles triangles having included angles of 150 deg, as shown in Fig. 3. The precision reference specimens are not intended for use in visual or tactual evaluations of finishes since they do not have the appearance or characteristics of commonly produced surfaces.

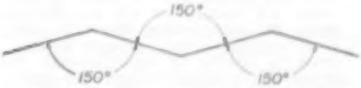

Fig. 3. Profile of Precision Reference Specimen

Cast Surfaces

Micro-inch roughness designations with instruments in current use for measuring other types of surfaces have been found unsatisfactory for specifying finishes on as-cast surfaces. A technical committee of the Aircraft Industries Association has recently published a tentative specification for a cast surface comparator, which enables visual and tactual comparison between production castings and the standard surfaces of the comparator (Fig. 4). Table II gives the approximate micro-inch equivalents for the "C-numbers" of the cast surface comparator.

Selection of Surface Finish

Considering roughness as the only surface requirement, four classes of application may be distinguished:

1. Parts for which a specific range of roughness, or a specific kind of roughness, produces the best performance.

Table I. Recommended Values of Roughness and Waviness

Roughness Height, micro-in.				
0.25	5	20	80	320
0.50	6	25	100	400
1	**8**	**32**	**125**	**500**
2	10	40	160	600
3	13	50	200	800
4	**16**	**63**	**250**	**1000**

Waviness Height, micro-in.					
20	80	300	1,000	5,000	15,000
30	100	500	2,000	8,000	20,000
50	200	800	3,000	10,000	

Bold-faced numbers are preferred values of roughness height.

ASM Committee on Surface Finish

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Manager, Research Laboratory
SKF Industries, Inc.

G. Carvelli
Engineering Dept.
Wright Aeronautical Div.
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Thompson Products, Inc.

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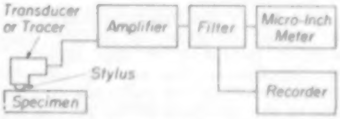


Fig. 2. Instrumentation for Measuring Surface Roughness

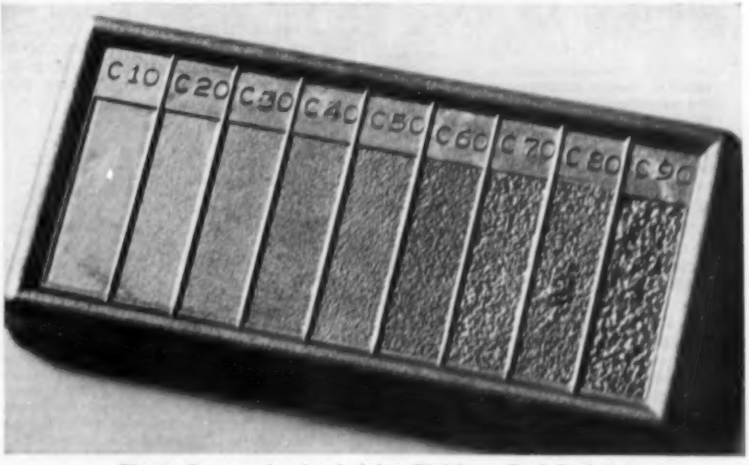


Fig. 4. Comparator for Judging Finish on Cast Surfaces

Table II. Comparison of Roughness Designations for Cast Surfaces

C-Number[a]	Approximate Micro-Inch Equivalent
C-10	20
C-20	60
C-30	120
C-40	200
C-50	300
C-60	420
C-70	560
C-80	720
C-90	900

(a) See Fig. 4.

Surfaces either smoother or rougher than the optimum range will interfere with the performance of parts in this class. An example of this is cylinder bores for automotive, diesel or aircraft engines. Also, ground finishes prior to honing or superfinishing, if smoother or rougher than the optimum range, will be difficult or impossible to hone or superfinish.

2 Parts that perform better, the smoother the surface, and for which the engineer's specification of roughness is a compromise between the cost of finishing and the added improvement in performance obtained as a result of more costly finishing. Examples are component parts for antifriction bearings, and the cam face of valve tappets.

3 Parts for which the smoothest finish possible is desired, irrespective of cost or present availability. Examples are large telescope lenses and some plug gages.

4 Parts which, for reasons of manufacturing policy, are specified to have roughness no greater than a certain maximum, even though the service performance of the part would not be affected adversely, or would be affected only slightly by exceeding the specified maximum. This is sometimes done as a matter of process control where production uniformity is desired for *all* parts because a majority of parts made on a given machine do require a definite roughness produced in a definite way.

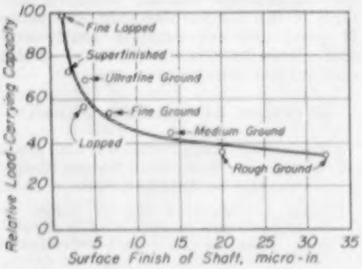


Fig. 5. Load-Carrying Capacity of Journal Bearings as Related to Surface Roughness of Shaft (W. E. R. Clay)

Many surfaces, of course, do not require any control of quality, and the specification of a maximum roughness for such parts would serve no practical purpose and would cause needless expense. Such surfaces usually include drilled holes, counterbored holes, pipe threads, spotfaces, broached keyways and splines, chamfers, screw slots, bolt heads, cutoff surfaces and sawed slots.

A relationship between surface finish and performance or appearance determines the need for a specification. Once the need has been established, the engineer must decide which of the processing methods capable of producing the required finish will be used. In many instances, the choice will be made from available equipment rather than from equipment that is exactly suited.

Finish and Performance

Resistance to wear and fatigue are two important characteristics influenced by surface finish. A change of about 30% in roughness is usually the least amount that will result in a measurable difference in wear, friction or durability of the surface. The effects of surface finish may be illustrated by reference to current practice on a few common parts.

Journals and Plain Bearings. The surface roughness of a journal, as for main and connecting-rod bearings, which commonly use babbitt, should be less than 12 micro-in. If a hard bearing such as bronze is used, and if the loading is high (more than 5000 psi), the roughness of the journal and bearing surfaces should be less than 8 micro-in. for best serviceability.

The effect of surface roughness, especially below 12 micro-in., is a significant factor in the load-carrying capacity of a journal bearing. Data for a particular combination are shown in Fig. 5.

Waviness is important, measured both in the direction of the axis and in a circumferential direction. With bearing loads of 2000 psi or more, waviness of 0.0001 in. in the axial direction of the journal will cause early fatigue failure of the bearing. Waviness height in the circumferential direction should not exceed 0.0002 in. for a wave length of 1 in. or more. If these waves are shorter than 1 in. in length, waviness height should be further reduced. The drawing should specify limitations on the waviness in each direction when necessary. The usual tolerances on the diameter are insufficient to take care of this problem.

The lay of the machine marks must be in the direction of motion. However, if produced by fine lapping, a multidirectional lay can be tolerated. Thrust bearings are particularly sensitive to the direction of lay on the contacting surface, unless the loading is extremely light. For example, if the thrust face of a steel crankshaft is coarse ground by the side of the grinding wheel, the surface produced may cause rapid failure of the bearing. For best results such thrust surfaces should have a roughness less than 20 micro-in. if turned, and the markings should run circumferentially on the part.

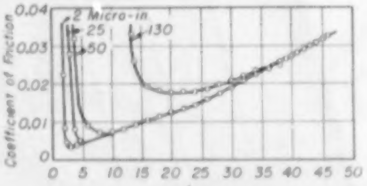


Fig. 6. Effect of Surface Finish on Friction with Hydrodynamic Lubrication Using a Flat Slider on a Rotating Disk. Z equals oil viscosity, in centipoises; N is rubbing speed, in fpm and P is load, in psi.

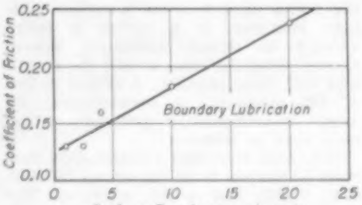


Fig. 7. Effect of Surface Roughness on Friction under Conditions of Boundary Lubrication

If a machined finish prevents adequate lubrication of journal bearings, it is not unusual to shot peen or otherwise provide a controlled degree of roughness of the journal surface before the last machining operation. After the final finishing by machining, the journal surface is then made up of plateaus, having a prescribed surface roughness, and minute voids between these plateaus to carry additional lubricant for use on the contacting surfaces.

In specifying the surface finish for journals and bearings the type and viscosity of the lubricants to be used should be considered. Lubricants of higher viscosity, which have improved load-carrying capacity, allow the use of rougher surfaces because the thicker film of lubricant is more effective in preventing metal-to-metal contact.

Table III. Statistical Limits for Sampling Surface Roughness (Micro-In.)

Max Allowed	Normal Average (to hold under max)	Control Limits Average, + and −	Average Range
6	4.2	1.8	1.7
8	5.6	2.4	2.3
10	7.1	2.9	2.8
12	8.5	3.5	3.4
15	10.7	4.3	4.2
20	14.3	5.7	5.6
25	17.7	7.3	7.1
30	21.3	8.7	8.5
35	24.9	10.1	9.9
45	32.0	13.0	12.7

Samples of 3 pieces, instrument reading

Piston Pins. The surface finish requirements and dimensional tolerances on a piston pin are more exacting than on most other comparable journal bearings. The important surface is the outside diameter, which must be round and straight within 0.0001 in. Allowable fits between piston and pin (or between rod and pin in a floating type of design) can be determined only experimentally; in automotive engines, these fits are usually in the range from 0.0003 to 0.0005 in.

For operation at high loads with hard bearing materials, piston pins usually have roughness below 8 micro-in.; 2 to 4 micro-in. is common.

Under severe conditions of loading, with extremely hard bearing materials, one approach to satisfactory bearing operation has been to have small depressions (such as can be produced by shot peening or grit blasting) in the surface. After peening or blasting, the pin is lapped to remove the metal that has been pushed above the nominal surface. The resulting surface is smooth with numerous small depressions to hold oil for peak loads on the surface. The over-all roughness may be as high as 16 micro-in., with 8 micro-in. on the plateaus; however, the character of the surface is more important than the roughness value in these applications.

Cylinder Bores in automotive, diesel and aircraft engines usually have a roughness between 16 and 40 micro-in. Smoother finishes retard proper seating of the rings. Coarser finish will accelerate initial wear and oil consumption and may accelerate wear throughout the life of the barrels. The early break-in period is crucial and is influenced greatly by the initial surface finish. A highly burnished or polished surface will scuff or gall, while a dull, honed finish will usually perform satisfactorily. Various turned and ground finishes have been used but these are slow to break in, causing excessive oil consumption.

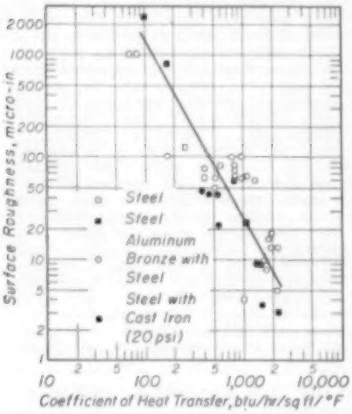


Fig. 8. Effect of Surface Roughness on Heat Transfer across an Interface for Several Combinations

The preferred lay on cylinder bores is an X-configuration typical of the finish obtained by honing. If this pattern cannot be obtained, then the lay should be in a circumferential direction; it should never be in the direction of motion.

Cams and Tappets. Working faces of tappets are usually finished to about 6 micro-in. In a few applications, shot peened steel tappet faces seem to retain lubricant slightly better than unpeened surfaces. Cam surfaces are usually ground to about 16 micro-in. max.

Valve Stems are usually ground to a roughness of 12 to 40 micro-in.; rougher surfaces are used under certain conditions as an aid to lubrication.

Valve Guides. Broached surfaces not only may be too smooth for retention of oil but if any galling occurs during the broaching operation, it is parallel to the action of the valve, which further reduces oil retention. Satisfactory lubrication is obtained with reamed surfaces, which have shallow circumferential grooves that retain oil.

If statistical sampling is used in controlling surface finishes, normal averages, control limits, average ranges, and upper limits of range must be established. An example of such statistical limits is given in Table III.

Antifriction Bearings. The effect of variation in surface finish becomes a factor when attempting to hold close dimensional tolerances. Since with rougher finishes there is more variation, it becomes necessary to obtain smoother surface finishes when close dimensional tolerances are required. A suggested relation between tolerance and surface finish for antifriction bearings is given in Table IV.

Table IV. Relation of Dimensional Tolerance to Surface Finish of Antifriction Bearings

Dimensional Tolerance, in., + and −	Surface Finish Range, micro-in.
Less than 0.0002	Less than 5
0.0002 to 0.0005	5 to 9
0.0005 to 0.0020	9 to 27
0.0020 to 0.0050	27 to 54
0.0050 to 0.010	36 to 90
More than 0.010	No relation

There are no standard surface finish specifications for shafts and housings for use in conjunction with antifriction bearings. Values suggested by one manufacturer, to be used with bearing bores and outside diameters of various roughnesses, are listed in Table V.

Noise in ball and roller bearings is caused by dirt, misalignment, corrosion, surface damage, surface roughness, geometrical inaccuracy and other factors. Often the mountings used are not conducive to quiet operation.

Current manufacturing techniques are capable of consistently producing surface finishes of the various components in the range from 0.5 to 1.0 micro-in. on bearing balls and 1 to 6 micro-in. on the ball grooves of outer and inner rings.

The table at the end of this article shows finish and other data for antifriction bearings, for cylindrical objects and other common parts.

Friction

The effect of surface finish on friction, with a complete hydrodynamic oil film and when the surfaces are just beginning to break through the film, is illustrated in Fig. 6. Figure 7 relates the coefficient of friction to surface roughness under conditions of boundary lubrication.

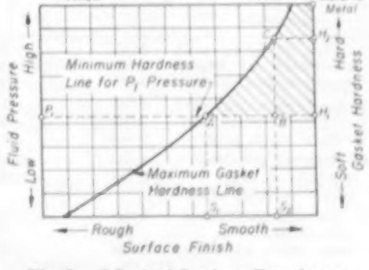


Fig. 9. Effect of Surface Roughness on Pressure Tightness of Gasketed Joints. For pressure P_1, *minimum hardness is* H_1. *The shaded portion of the chart is the usable range of surface roughness and gasket hardness for* P_1 *pressure. To seal* P_1 *pressure,* S_1 *would be the roughest surface finish allowable, as the maximum and minimum hardness lines cross at point A. With a smoother surface* S_2, *the extended range of gasket hardness made available is indicated by points B and C. The lower hardness limit,* H_1, *does not change for* P_1 *pressure, but the upper limit would be* H_2.

Figure 8 shows that heat transfer may be changed by a factor of ten, depending on the roughness of the contacting surfaces.

Tightness of Joints

The relationship of surface roughness to pressure tightness of joints is sometimes a problem. Because joined surfaces fabricated by high-production methods cannot be made flat or smooth or tight enough to seal fluids or gases, some kind of gasket material or sealer is needed to obtain joint tightness. Many kinds of high-pressure units in operation have been sealed without the use of gasket materials; however, the surfaces that are required (extremely low waviness and 1 to 2 micro-in. roughness) to provide seals are not normally attained in automotive items or others fabricated on a high-production basis.

Table V. Typical Surface Finishes for Shafts and Housings[a]

Bearing ID	Shaft	Bearing OD	Housing
7 to 11	11 to 18	7 to 11	9 to 14
14 to 22	18 to 29	11 to 14	14 to 22
22 to 29	29 to 40	14 to 22	22 to 32

(a) Surface roughness suggested by one manufacturer of antifriction bearings for use on shafts and housings when mated with bearings of various finishes.

For mounting practices of shaft-to-bearing-bore fits that are mean to several 0.0001 in. tight, and housings varying from mean to several 0.0001 in. loose

In order to define the general conditions of surface finishes that require some type of sealer, the following factors must be considered: temperature and pressure of operation; type of fluid or medium to be sealed; type of surface to be sealed and its requirements of compressibility, resilience, flow, shape or thickness.

Figure 9 illustrates the application of two general rules for determining roughness requirements of surfaces that are to be sealed when container pressures are involved. These rules are:

1. When the surface roughness and waviness diminish, the gasket thickness can be decreased and the unit bolting load should be adjusted, depending on the surface to be sealed for any constant surface area.
2. When the surface roughness and waviness are increased, the gasket thickness should be increased and the unit bolting load should be adjusted according to the surface to be sealed, while maintaining recovery compression on the sealing material for any constant surface area.

As a further guide in determining the type of surface to use when two or more joints require sealing, the following effect of the variables should be considered: (1) When temperatures exceeding 250 F are involved, less resilient and less compressible materials must be used than are normal for lower temperatures, and the surface roughness and waviness of these must be decreased; (2) smooth surface finishes are required to seal high-pressure units because the required sealing materials have high tensile strength and low compressibility; and

Table VI. Comparative Performance of Tools with Ground and Honed Surfaces

Part Being Machined[a]	Pieces per Grind: Ground Tools[b]	Pieces per Grind: Honed Tools[c]
Gear	13	200
Gear	30	400
Shaft	30	200
Gear	10	40
Gear	15	40
Ring	20	50
Shaft	15	100
Gear	18	100
Shaft	8	40
Shaft	6	50

(a) All parts made of SAE-AISI 3312 or 3315 steel and machined at Brinell hardness number 187 to 235. Steel tools were hardened to Rockwell C 61 to 65. (b) Surface of cutting contact ground to roughness between 20 and 80 micro-in. (c) Cutting contact honed to between 1 and 2 micro-in.

Table VII. Effect of Machining Variables on the Roughness of Turned Surfaces

Increase in:	Causes Finish to:
Cutting speed	Improve
Feed	Deteriorate
Depth of cut	Deteriorate
Back rake	Improve
End relief angle	Deteriorate
Nose radius	Improve

Based on data compiled by N. E. Woldman and R. C. Gibbons

Table IX. Surface Roughness Guide for Turning with Carbide Tools

Shape of Tool[a]	Feed, in. per rev	Roughness, micro-in.
1	0.030	600
1	0.020	400
2	0.012	100
3	0.003	40

(a) The form of the carbide-tipped cutting tools used to produce the above roughness values are shown below. The radii of tools 2 and 3 below were finished with a No. 300 diamond hone.

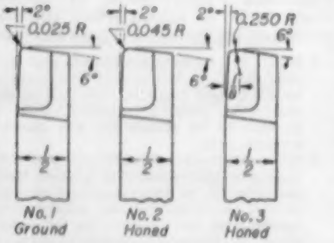


Table X. Typical Surface Finishes Obtained on Piston Pins with Centerless Grinding and Lapping

Operation	Total Stock Removed, in.	Dim. Tol.[a]	Micro-In.
Centerless Grinding			
Rough Grind	0.0045	0.00025	...
Rough Grind	0.002	0.00025	...
Semifinish Grind	0.0016	0.00015	13 to 16
Centerless Lapping			
Rough Lap	0.0005	0.00005	7 to 9
Rough Lap	0.0003	0.00005	5 to 6
Finish Lap	0.0001	...	2 to 4

(a) Dimensional tolerance, in. + and −

Table XI. Typical Relations Between Stock Removal and Surface Finish for Stone Finishing (Honing or Superfinishing)

Stock Removed by Stone Finishing, in.	Surface Roughness, micro-in.
0.00012	10
0.00020	15
0.00025	20
0.00030	25
0.00035	30
0.00040	35

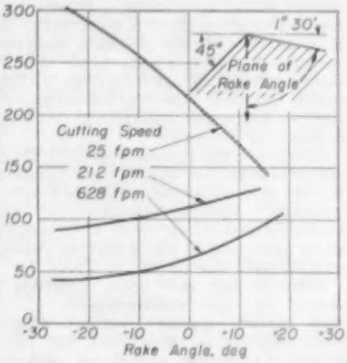


Fig. 10. Effect of Rake Angle on the Roughness of Turned Mild Steel Surfaces at Three Cutting Speeds with Carbide Tools. Depth of cut, 1/64 in.; feed, 0.006 ipr (A. J. Chisholm)

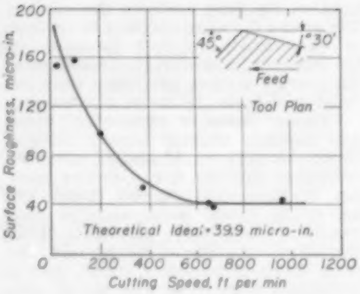


Fig. 11. Effect of Cutting Speed on Surface Roughness. Mild steel machined at 0.015-in. depth of cut, 0.006-in. feed, with carbide tools having end relief angle of 1 deg, 30 min and zero top rake. The theoretical ideal value at 40 micro-in. is that obtained if there is no built-up edge, from which it is expected that the surface profile of the workpiece will closely conform to the tool geometry and feed. The curve above (A. J. Chisholm) apparently becomes asymtotic to 40 micro-in. but it has been shown for carbide tools that the surface roughness again becomes greater with very high cutting speeds. These data are not necessarily valid for other tool materials. Roughness of aluminum turned with a diamond tool increases as cutting speed increases. High speed tools produce low roughness at about 10 fpm, rougher surfaces at higher speeds, and progressive improvement beyond these.

Table VIII. Surface Roughness of Rolls, and Time Required for Finishing

Class of Application	Method of Finishing	Method of Specifying	Surface Roughness, micro-in.	Relative Time to Finish Surface
Noncritical	Not machined	Surface as is, no machining	1800 to 225	0
Average	Lathe finished	Lathe finish	720 to 225	1 to 5
Critical	Ground or polished	Lathe finish, then grind or polish to remove tool marks	110 to 14	5½ to 9
Very critical	Superfinished	Superfinish	14 to 2	9 to 15

Table XII. Typical Relations between Stock Removal, Operating Conditions and Surface Roughness for Finish Grinding Carbon Steels and Low-Alloy Tool Steels

Operation	Total Stock Removed,[a] in.	Down Feed	Cross Feed	Work Speed, rpm.	Surface Roughness, micro-in.
Surface grinding with periphery of wheel, reciprocating work	0.002	0.0002 in.	0.031 in.	max	10
	0.005	0.0005 in.	0.062 in.	max	16
	0.010	0.0010 in.	0.250 in.	max	32
Surface grinding with ring-type wheel on rotary work table	0.005	0.004 ipm	.....	15	10
	0.005	0.008 ipm	.....	24	16
	0.010	0.016 ipm	.....	24	32
Cylindrical grinding, traversing, 2-in. diam work on centers	0.002	0.0002 in./pass	60 ipm	80	10
	0.005	0.0005 in./pass	60 ipm	100	16
Cylindrical oscillating plunge grinding, 2-in. diam work on centers	0.005	0.010 ipm	.....	150	10
	0.030	0.040 ipm	.....	150	16
	0.030	0.060 ipm	.....	150	32

(a) On diameter for cylindrical grinding

Table XIII. Waviness and Roughness Readings for Inner-Ring Roller Bearing Races after Grinding and after Superfinishing

Condition	Reading, micro-in.	
	Wavometer Readings	
	Low Band, 4 to 17 Waves	High Band, 17 Waves and Above
After grinding	1.5 to 2.5	5.0 to 7.0
After superfinishing	1.5 to 2.5	0.3 to 0.4
	Surface Roughness Readings	
	Across Race	Around Circumference
After superfinishing	1.5 to 2.0	1.0 to 1.5

(3) rough, wavy semifinished surfaces require highly compressible sealing materials with relatively light bolting pressures. Smooth finished surfaces, generally required for sealing high-pressure mediums, require thin gasket materials of low compressibility and relatively heavy bolting pressures.

Effect of Finish on Tool Performance

The following examples are typical of the available data concerning the effects of surface finish on performance of tools.

Cutting Tools. Tool life and performance are greatly affected by finish. Table VI shows the number of pieces obtained with ordinary ground tools, as compared with the output from ground and honed tools. The results are influenced not only by the keenness of the cutting edge, but also by the smoothness of the end, flank and chip-breaker groove of the tool. Under the microscope, the cutting edge appears as an irregular saw-tooth edge, which varies in roughness according to the abrasive wheel used and the grinding speed and feed. The roughness of a ground tool is usually from 20 to 80 micro-in.; roughness of a honed tool can be held to 1 to 2 micro-in.

An irregular saw-tooth edge and irregular surface produce an uneven flow of metal through the crevices; this condition creates stress concentration and localized heating of the tool point, both of which increase the rate of tool failure. Also, the roughness of the tool face produces increasing amounts of built-up edge on a tool and results in a rougher machined surface. Honing the cutting edge and surface will minimize this effect.

Other factors in machining that influence the finish obtained on machined surfaces are given in Table VII. Figures 10 and 11 show the effects of cutting speed and rake angle on the roughness of turned surfaces.

Coining Punches for producing a fine finish in the tapered hole of valve spring caps are made of hot work die steel, H12 or H13, carburized and hardened to Rockwell C 61 to 63 on the taper and form only. The punch, form-ground to a close dimensional tolerance and with the surface polished to a roughness of 9 to 13 micro-in., will produce as many as 500 pieces before failure by abrasion.

By improving the finish to 4 micro-in. max. on the form and areas subject to high coining pressures, service life can be doubled or trebled. Improvement in surface finish beyond 4 micro-in. does not increase tool life significantly. However, by maintaining the 4 micro-in. finish and plating 0.5 mil of hard chromium on the surface, punch life is as great as 35,000 pieces.

Die Components. Occasionally, specifications call for a tool finish unnecessarily smooth. For example, in a particular set of die components, consisting of extrusion sleeve, coining die punch, and die insert for forging automobile engine valves by the extrusion process, the tools were ground and the bore and angle of each sleeve and insert were polished to a finish of 7 to 9 micro-in. The life of these tools was 800 to 1200 pieces. Extrusion sleeves and die inserts ground to 18 micro-in. but not polished gave equal service life. Later the grinding operation was replaced by turning of the bore and the form with carbide-tipped tools at high speeds and fine feeds to give a finish of 31 micro-in. without impairing tool performance.

The coining dies also had been polished to 7 to 11 micro-in., but a machine finish of 31 micro-in. resulted in the same serviceability of the die. Valve forging dies, grit blasted to a surface finish of 27 to 36 micro-in. after hardening have been satisfactory.

Rolls. Finishes for rolls used in the textile, paper, plastics, rubber, woodworking and metalworking industries affect the cost of the rolls by as much as a factor of five when fine finishes are specified. The units of time required for various roll surface finishes are indicated in Table VIII. The specification "surface as is—no machining" is used chiefly on low-speed carrier rolls. The surface on such rolls will be no better than the commercial limits, if as good, with respect to size, roundness and straightness.

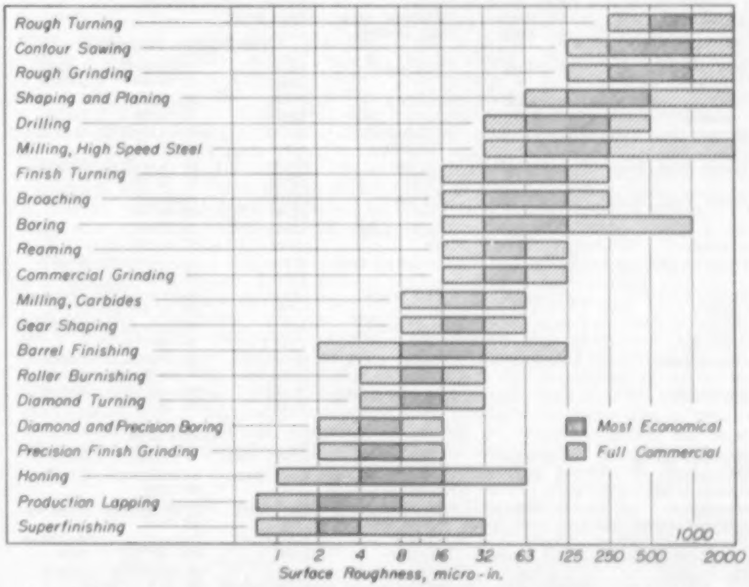
A large class of metal rolls requires no greater straightness and roundness than a lathe-finished surface, yet fine tool marks are objectionable. For these the specification is usually "lathe finish and polish to remove tool marks". Roughness is from 45 to 90 micro-in.

A definite micro-inch finish specification has significance at 50 and below. However, it is still necessary to take other factors into account, such as whether the finish is to be attained by emery polishing or grinding, the permissible amount of out-of-roundness and the straightness of the roll.

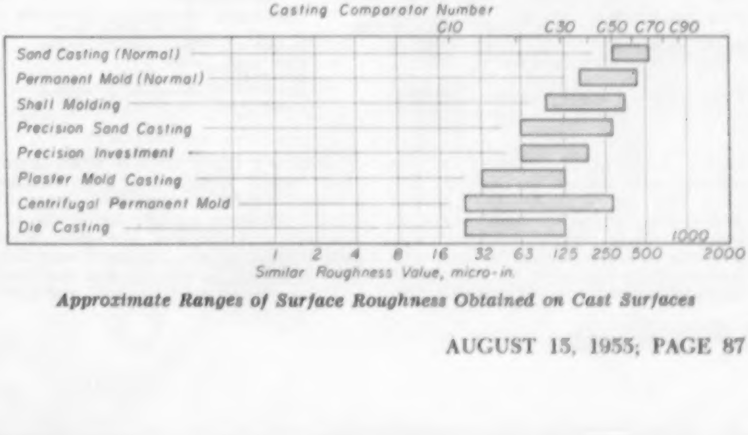
For example, it is easily possible to emery polish a lathe-finished surface to a smoothness of 20 to 50 micro-in. However, such a roll, while smooth, will have no greater accuracy than can be obtained from lathe finishing. When turning on centers, the surface of the roll may have a runout ranging from 0.003 to 0.010 in., depending on the material and size of the roll. On the other hand, an applicator roll may be required to spread a film only a few tenths of a mil thick. A 10-micro-in. specification here would call for ground journals and ground surface to the required smoothness but also with a tolerance on runout of perhaps 0.0002 to 0.0005 in. Roll finishes below 10 micro-in. are difficult and costly to produce and require methods such as burnishing, lapping and honing.

Influence of Processing Method

Since surface roughness depends almost entirely on the machining operations used, a knowledge of the roughness produced by the commonly em-



Approximate Ranges of Surface Roughness Produced by Various Machining Processes



Approximate Ranges of Surface Roughness Obtained on Cast Surfaces

Typical Surface Finishes on Machine Parts

Part	Size, in.	Function or Functional Movement	Metal	Hardness	Final Operation	Dimensional Tolerance, in.	Finish on Mating Part, micro-in.	Surface Roughness, micro-in.
Cylindrical Shapes								
Brake drum, friction surface	10.9975 diam, 2¼ long	Friction surface	Cast iron	Brinell 160 to 200	....	±0.0025	Brake lining	50 best 120 max
Crankshaft, main bearing surfaces	2½ diam	Bearing surface	Nodular iron	Brinell 217 to 269	Grind	±0.0004	Babbitt lining, 12 max	12 max
Crankshaft, main bearing surfaces	2.5000 diam, 1.874 long	Bearing surface	1046 steel	Brinell 228 to 269	....	±0.0005	Babbitt bearing	15 max
Crankshaft, main bearing surfaces	2.1884 diam	Bearing surface	Nodular iron	Brinell 217 to 269	Grind	±0.0004	Copper-lead bearing	12
Crankshaft pulley, hub, diam	1⅞ diam, 1¼ long	Surface for running oil seal	Cast iron	Brinell 163 to 229	Grind	±0.002	Rubber seal	40 max
Cylinder block, bore	3.8135 diam, 6½ long	Bearing and seal	Cast iron	Brinell 170 to 217	....	±0.001	Cast iron piston rings	15 to 20
Cylinder block, bore	3⅝ diam, 6 long	Bearing and seal	Cast iron	Brinell 179	Hone	±0.0024	Cast iron piston rings	20 to 35
Cylinder block, bore	3½ diam	Bearing and seal	Cast iron	Brinell 179 to 241	Hone	±0.0003	Aluminum alloy	25 to 35
Exhaust valve stem	0.3715 diam, 3.72 long	Bearing and seal	Cr-Mn steel	Rockwell C 34 min	....	±0.0005	Cast iron	18
Piston pin	0.9120 diam	Bearing surface	5015 carburized	Rockwell C 58 to 63	Lap	+0.0003 −0.0000	....	3
Piston pin	0.8592 diam, 2.885 long	Bearing surface	Mn steel carburized	Rockwell C 60	....	±0.001	Tin plated aluminum	4
Piston, piston-pin bore	1⅛ diam	Bearing surface	Aluminum alloy	....	Diamond turn	....	....	12
Piston, piston-pin bore	13/16 diam, ⅞ long	Bearing surface	Aluminum alloy	Brinell 90 to 120	Grind	±0.0003	....	50 max
Drive gear, oil pump	2½ diam	Rotating, 1450 rpm	8640 steel	Rockwell C 55 to 60	Grind sides 0.0001 concave	±0.0005 thick	Bronze bearing plates	7
Shaft	1½ diam, 1¼ long	Interference fit	C 1118 Steel	....	Grind	±0.0008	Same as on shaft	40 max
Shaft	1¼ diam, 2½ long	Light load at 1400 rpm	4140 steel	Brinell 228 to 255	Grind	±0.0001	Bronze bushing, 25 max	25 max
Shuttle valve, transmission	0.4368 diam, 0.344 long	Oil seal	Molybdenum steel	Rockwell C 58 min	....	±0.0002	Al die casting, anodized, 20	10
Valve body	1½ diam, 5½ long	Sliding, slow, for O-ring	Cast iron	....	Hone	±0.0005	4615 ground, 16 max	10 max
Antifriction Bearings								
Bearing ball, grade 1	Various	Rolling	52100 steel	Rockwell C 62 to 64	Lap or polish	Sphericity 0.000025	See races	1.5 max
Bearing ball, special	Various	Rolling	52100 steel	Rockwell C 62 to 64	Lap or polish	Sphericity 0.000010	See races	0.05 to 1.0
Outer, ring, diam	2.8341 diam	Fit into housing	52100 steel	Rockwell C 62 to 64	Grind	+0.0005	Same as on ring	20 max
Inner ring, bore	1.1807 diam	Fit on shaft	52100 steel	Rockwell C 62 to 64	Grind	+0.0004	....	30 max
Inner ring, bore	1.1809 diam	Fit on shaft	52100 steel	Rockwell C 62 to 64	Grind	+0.0002 −0.0000	....	10 max
Inner race, groove	Various	Ball track	52100 steel	Rockwell C 62 to 64	Polish	±0.0010	Bearing balls	6 max
Inner ring, face	....	Locating face	52100 steel	Rockwell C 62 to 64	Hydro-lap	+0.000 −0.0010	....	8 max
Outer race, groove	Various	Ball track	52100 steel	Rockwell C 62 to 64	Grind	±0.0010	Bearing balls	10 max
Outer race, groove	Various	Ball track	52100 Steel	Rockwell C 62 to 64	Polish	±0.0010	Bearing balls	6 max
Outer race	Various	Roller track	52100 steel	Rockwell C 59 to 61	Superfinish	±0.0010	....	3 max
Outer ring, face	....	Locating face	52100 steel	Rockwell C 62 to 64	Grind	+0.000 −0.002	....	20 max
Other Parts								
Bumper parts	Various	Decorative	Sheet steel	....	Buff	....	....	5 to 8
Camshaft, cam lobes	⅝ wide	Lift intake and exhaust valves	Cast iron	Scleroscope 40 min	Grind	±0.0002 per deg lift	5120 hardened, 6 max	16 max
Camshaft, cam surface	⅛ wide	Bearing surface for tappet	Cast iron	Scleroscope 65 min	....	....	4 (on valve tappet)	20 max
Crankshaft, thrust surface annulus	2½ to 3.44 diam	Thrust surface	Nodular iron	Brinell 217 to 269	Machine turn	±0.002	Babbitt bearing, 12 max	25 max
Cross slide	1¼ by 5½	For sliding heavy loads	4615 steel	Rockwell C 60	Grind	±0.001	Same as slide	16 max
Cutter slide	½ by 3	For sliding light loads	4140 steel	Brinell 269 to 302	Mill	±0.002	Same as slide	100
Cylinder block, top	7¼ by 17¼	Surface for head gasket	Cast iron	Brinell 179	Broach	±0.004 flat ±0.002 in 6 in.	Low-carbon steel	90 max
Flywheel, annulus	4⅞ to 10⅝ diam	Face for clutch disk	Cast iron	Brinell 179 to 235	Machine turn	....	Woven asbestos	80 to 120
Stator blade, jet engine compressor	1 by 5 by ⅛ thick	Deflect air	Powdered iron (plus copper)	Rockwell B 100	Polish	±0.006 thickness	(Air)	9
Valve tappet, cam face	....	Sliding, light load	5120 steel	Rockwell C 58	Grind	±0.001	Iron, 16 max	6 max

ployed methods is essential to the realistic specification of surface finishes. The bar graphs on the previous page indicate the commercial ranges. As shown in these graphs, similar roughness can be obtained by more than one method. Since a range of finishes can be obtained by each method, the selection of a surface finish involves much more than merely designating a particular process. Other factors that have a strong influence include the shape of the part and the tool, the speed and feed of cutting, the lubricant, and the alloy being cut, in turning, and the type of wheel, rate of stock removal, and material the part is made of, in grinding.

A full discussion of the effect of process variables in the 21 methods shown in the bar graph is beyond the scope of this article. A few relations between the conditions of metal removal and the roughness produced, for four methods, are given in Tables IX to XIII.

Residual Stresses

By the ASM Committee on Residual Stress

Subdivisions

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ASM-SLA Q25

RESIDUAL STRESSES, frequently called "locked-up" stresses or "internal" stresses, are those existing in a body free from external forces.

Residual stresses are developed in metals to some degree by every commercial fabricating process: welding, casting, heat treating, forming, machining, grinding, plating, and others. Specifically they are created by any process that effects a nonuniform change in shape or volume throughout a workpiece. Thus, shot peening develops residual stresses in a metal because it spreads the surface layers but not the interior. The distended surface layers being restrained by the interior are held in compression; the unworked interior being stretched by the distended surface is in tension.

Residual stresses in metals are important because of their manifold and diverse effects. Residual stresses can cause metals to crack quickly and catastrophically when exposed to certain atmospheres—industrial, marine, rural or artificial—or to liquids (stress-corrosion cracking) or to liquid metals, or when heated (fire-cracking), when aged (stress-precipitation cracking) or when cut into. Residual stresses can cause metals to warp when machined or cut (and thereby cause such secondary effects as binding and breaking of reamers). Depending on their nature and distribution in a metal, residual stresses can delay or hasten fatigue failures. Fortunately, the magnitude and direction of the residual stresses in metals can be changed so as to avoid difficulties or gain advantages.

Residual Stress Patterns

Because temperature changes can expand or contract a metal volumetrically, either directly through thermal expansion or indirectly through phase changes, residual stresses are developed when heat is put into or taken out of a metal inhomogeneously. Common examples where residual stresses result from effects of thermal expansion alone (that is, where phase transformations are not involved) include:

Spot Welding. Residual stresses are developed in sheet metals that are spot welded, according to the pattern shown in Fig. 1. The temperatures in the hot spot will affect the magnitude of the stress found in this pattern, but often the weld spot gets hot enough for the residual stresses across the spot itself to equal the yield strength of the metal at that point.

Butt Welding. Two free plates butt-welded along one edge will contain residual stresses of the pattern shown in Fig. 2. Welding temperatures are high enough for the residual stresses along the joint to approximate the yield strength of the metal. Electric-arc welding confines the stresses to a narrow region adjoining the weld itself. Gas-torch welding, with more diffuse application of heat, spreads the stresses out over a broader area.

Quenching. Cooling hot metals without phase transformation will produce compressive residual stresses at the surface of the piece and tensile stresses in the interior. Two specific examples of this generalization are given in Fig. 3 and 4 for a quenched cylinder and a quenched flat strip, respectively. Patterns developed in more complicated shapes can be synthesized from these with a little common sense and imagination. For example, the residual stress in a quenched tube can be imagined to result from wrapping the sheet of Fig. 4 around a mandrel. This gives the pattern of Fig. 5. Naturally a tube may be quenched with its ends plugged, in which circumstance the residual stress pattern is like that given in Fig. 6; or it may be quenched from the interior only, the residual stress pattern for which is given in Fig. 7.

The actual value of the peak stresses will be higher the higher the quenching temperature, the more drastic the action of the quenching medium, the lower the thermal diffusivity of the metal, the larger the absolute dimensions of the piece, the higher the modulus of elasticity, the higher the yield strength of the metal, and the higher the coefficient of thermal expansion. There are formulas that presume to relate these factors quantitatively to the magnitude of stress developed in the part, but they are cumbersome to use and are based on theoretical considerations that have not been fully tested.

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Here are some common examples where residual stresses result from phase transformation brought on by heat treatment:

Precipitation. When a dispersed phase is precipitated by heat treatment (as in aging) residual stresses will be developed around each particle of precipitate because of the difference in density of the precipitate and the matrix from which it formed. If the precipitate is more voluminous, the matrix will be placed in tension tangentially (the radial stresses being compressive) and the precipitate will be put in compression. Under these circumstances aging can cause cracking (especially when residual tensile stresses are already present from other sources); the fracture courses through the matrix that is under tension. Copper-chromium alloys belong to this class. If the precipitate is more dense, the matrix will be placed in compression and the precipitate will be in tension. In such alloys cracking does not run through the matrix. Because of aluminum's lightness, the matrix of aluminum alloys is usually thrown into compression; hence their general immunity to cracking during aging.

Bulk Transformations. In addition to the residual stresses developed by contraction accompanying cooling, residual stresses may also be developed by the transformations that occur during cooling. The most common example of this class of transformations, of course, is the decomposition of austenite in steels. Whether the decomposition involves the formation of pearlite, bainite or martensite, the metal expands. Because the time and temperature ranges for these reactions can be shifted at will by alloying, and because quenching rates can be varied with each piece, the residual stress patterns introduced into such a simple geometric shape as a solid round bar can take on any shape (compatible with rotational symmetry and self-equilibration). Figure 8 shows examples.

In Fig. 8(*a*) the quenching rate was such that the entire bar was converted to martensite. When the outside of the bar transformed to martensite and expanded, the warm soft austenite in the inside followed this deformation plastically. When the inside of the bar transformed to martensite and expanded, the cold, hard outside was stretched elastically. Thus the exterior

Supersedes the article on page 237 of the 1948 ASM Metals Handbook

was put in tension; the interior, in compression; final residual stress pattern is shown in Fig. 8(b).

In Fig. 8(c) the outside and inside both expand at about the same time (the outside by transforming to martensite, the inside by transforming to pearlite). The middle annulus of warm austenite follows the expansion plastically, then finally transforms to bainite, expanding as it does so and throwing the outside and inside into tension. Further cooling of the pearlite interior may increase the tension there as outlined in the paragraph "Quenching", giving the final residual stress pattern shown in Fig. 8(d).

Figure 8(e) treats one final example: the outside expands martensitically at about the time when the middle and interior expand pearlitically. Any inequalities in deformation at this point are accommodated by the plastic deformation of the hot austenite or pearlite. Finally the middle and interior pearlite cools and contracts, producing a normal contraction type of residual stress pattern (see paragraph "Quenching") as shown in Fig. 8(f). This latter reaction almost certainly occurs in the quenching of any plain carbon steel in sizes larger than an ordinary lead pencil, and accounts for the fact that such steels in large sizes always show a plain contraction type of residual stress pattern whether quenched from below or above the austenitizing temperature.

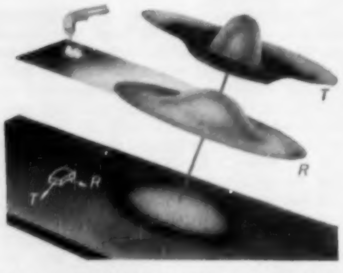

Fig. 1. Residual Stress Pattern Found in Strip Heated Locally, with No Phase Transformation Occurring. In the lower plane the direction is defined in which the radial stresses, R, and tangential stresses, T, operate. The intensity of the radial stress at different points throughout the strip is shown in the three-dimensional graph immediately above the strip; the stresses are tensile at the center of the affected zone and drop off to a negligible value at some distance from the affected zone. The intensity of the tangential stress at different points is shown in the chart: the stresses are tensile at the center of the affected zone, drop to a compressive value immediately outside the affected zone, and then fall off to a negligible value at some distance from the affected zone. Simple stress states demand equal radial and tangential stresses at center.

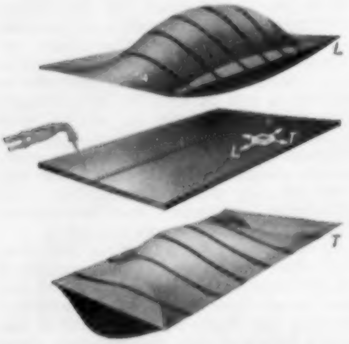

Fig. 2. Residual Stress Pattern Found in a Butt-Welded Strip. The middle drawing helps define what is meant by longitudinal stresses, L, and transverse stresses, T. The variation of the longitudinal stresses, L, is shown in the upper drawing; that of the transverse stresses, T, is in the lower drawing. Points above the white reference planes are tension; those below, compression. Pattern is for thermal effects without phase transformation.

The possible sequences of expanding and contracting that the outside, middle and inside of a round bar can follow during austenite transformation in a quench are so numerous that each set of conditions should be analyzed individually. Residual stress patterns resulting from localized heat treatments include the following:

Induction Hardening. A relatively shallow outside layer is heated and quenched to martensite in induction surface hardening. The formation of martensite is accompanied by a volume expansion that gives rise to surface compressive stresses and tensile stresses in the interior as in the expanded surfaces in shot peened articles noted above. The stresses are compressive at the surface, irrespective of the alloy content or the case depth. Oil quenching gives slightly weaker stress patterns than water quenching. A specific example is given in Fig. 19 of the article on page 120 of this Supplement.

Flame Hardening. This process is the same thermally as induction hardening. Compressive stresses exist at the surface. The actual stress pattern beneath the surface is still a matter of controversy, as are effects of time under the flame and the size of the piece.

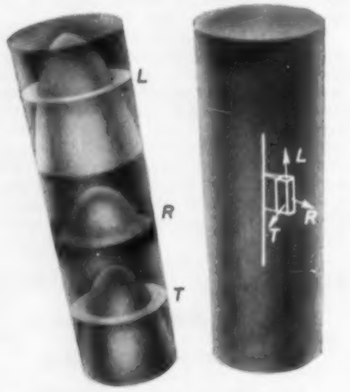

Fig. 3. Idealized Residual Stress Patterns Found in Quenched Cylindrical Bars if No Phase Transformation Occurs. In the figure at the right the directions of action are defined for the longitudinal stresses, L, the tangential stresses, T, and the radial stresses, R. The figure at the left is a three-dimensional chart showing the stress distribution found in quenched bars; the longitudinal stresses, L, at the surface of the bar are compressive (compressive stresses are indicated by points below the reference cross section); radial stresses, R, are nil at the surface of the bar and rise to tensile values at the axis of the bar; tangential stresses, T, follow a pattern similar to that of the longitudinal stresses.

Carburizing. Like induction and flame hardening, carburizing hardens only a thin surface layer, but carburizing can produce entirely different stress patterns. In carburizing, the entire piece is heated to the austenitic range—where carbon is absorbed at the surface — and then is quenched. The final residual stress pattern will now be influenced by the behavior of the surface, which normally will produce compressive stresses at the surface, and the behavior of the interior, which, depending on its transformation characteristics and cooling rates, can produce either compressive or tensile residual stresses at the surface.

Nitriding. The nitriding process is essentially the absorption of nitrogen into the surface layers of the steel, resulting in a tendency of the nitrided area to increase in volume. The growth tendency is restrained by the interior metal, which still has a relatively high yield strength at the nitriding temperature of about 1000 F. This process, therefore, causes residual compressive stresses in the surface of the steel.

Built-Up Shafts. In the absence of any phase transformation effects, a built-up shaft will develop tensile stresses in the exterior jacket: the cooling metal deposit and heated substrates are prevented from contracting by the cold, hard interior and, being thus distended, remain in tension. (To preserve equilibrium, the interior is in compression.) Figure 9 shows the residual stress pattern typical in plain carbon steel shafts of 1 to 4-in. diam when built up from 3 to 9%. Deposits in which phase transformations occur must be considered individually.

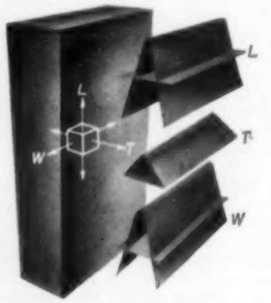

Fig. 4. Idealized Residual Stress Patterns Found in Quenched Flat Slabs When No Phase Transformation Occurs. In the figure at the left the directions of action are defined for the longitudinal stresses, L, width stresses, W, and thickness stresses, T. The figure at the right is a three-dimensional chart showing the stress distribution found in a quenched flat slab: the longitudinal stresses, L, at the surface of the slab are compressive (compressive stresses are indicated by points below the reference cross section), rising to tensile values on the center plane of the slab; thickness stresses, T, are nil at the surface of the slab and rise to tensile values at the center plane of the slab; width stresses, W, follow a pattern similar to that of the longitudinal stresses. These idealized patterns break down along the edges and corners and at the ends of the slab.

Castings normally would have compressive stresses at their surface and tensile stresses in the interior, just as a quenched cylinder would. Two factors arise in casting procedure which complicate the situation beyond simple quenching processes, however. One factor consists in the mechanical restraint which the mold offers to the shrinking casting. This factor is of little consequence in sand molds but in permanent molds or dies it becomes important. These effects will vary with each individual mold design. The other factor consists in the artificial cooling rates the foundryman introduces into his casting by chills, washes or other devices. These will distort the residual stress pattern developed in castings as opposed to their quenched analogues.

The effects of casting design may be pronounced. The basic factor seems to be the cooling rates of the different parts of the casting. Greatly different cooling rates in various parts of the piece will naturally produce a very complex pattern of residual stresses. Two examples of high residual stresses in as-cast gray iron are presented in Fig. 16 on page 33 of this Supplement.

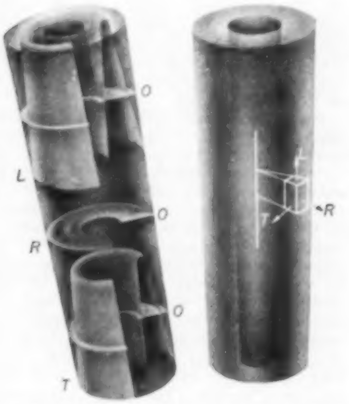

Fig. 5. Idealized Residual Stress Patterns Found in Quenched Tubes if No Phase Transformation Occurs. The directions of the longitudinal stresses, L, radial stresses, R, and tangential stresses, T, are shown at the right. Their distribution in a tube quenched from the inside and the outside is shown in the figure at the left.

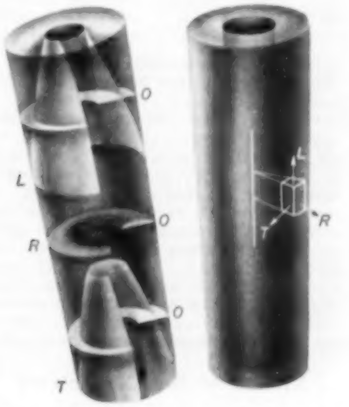

Fig. 6. Idealized Residual Stress Patterns Found in Tubes Quenched from the Outside, if No Phase Transformation Occurs. The directions in which the longitudinal stresses, L, radial stresses, R, and tangential stresses, T, operate are shown in the figure at the right. Their distribution in a tube quenched from the outside is shown at left.

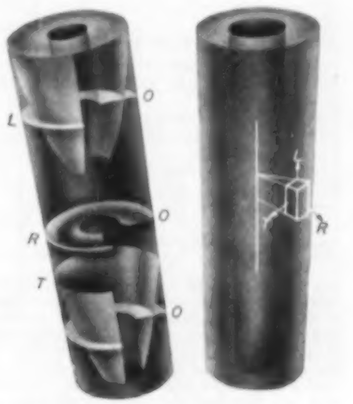

Fig. 7. Idealized Residual Stress Patterns Found in Tubes Quenched from the Inside. The directions in which the stresses L, R and T operate are shown in the figure at the right. Their distribution in a tube quenched from the inside only is shown at the left in the same way stresses have been shown in the previous illustrations.

Mechanical Processes

Mechanical working processes that develop residual stresses include:

Bending. Plastically bending a bar and then releasing the bending moment produces a saw-toothed distribution of longitudinal stresses (Fig. 10).

Single Pressure Spot. Thin sheets subjected to a single pressure spot (as in cold pressure welding) have a residual stress pattern of the type shown in Fig. 11. The pressure area expands laterally against the surrounding elastic sheet, stretching it and giving rise to tensile hoop stresses (but compressive radial stress) there. A single pressure spot on one surface of a thick chunk of metal (as produced by a gouge or service bruise) will still yield this pattern near the surface, although it dies out in subsurface layers.

Shot Peening, Surface Hammering, Surface Rolling and other such processes all expand the surface. The interior holds back this expansion, keeping the surface in biaxial compression and the interior in biaxial tension. It should be noted that a single pressure area on a surface can produce tensile stresses in some regions on the surface (see the preceding paragraph) while many pressure areas produce compression on the surface. One blow in shot peening, for example, that is much heavier than the average, will leave tensile stresses around it and defeat the purpose of shot peening.

These processes produce compressive stresses to a shallow depth—a few ten thousandths to a quarter of an inch with current methods.

In shot peening, the maximum compressive stress will amount to about half the yield strength of the metal. This compressive zone is biaxial. It will run deeper the greater the shot velocity, the heavier the shot and the softer the base metal. Some of the limiting conditions in shot peening are interesting. Tumbling in alundum abrasive for 10 min produces surface compressive stresses of −15,000 psi with ½ to ¾-in. grit size and −50,000 psi with 1 to 1½-in. grit size, while a 4-hr tumbling produces stresses of −60,000 and −75,000 psi, respectively. Even soft shot will induce compressive stresses in hard surfaced metals—a carburized steel (Rockwell C 60) can be shot peened to −120,000 psi residual stress at the surface with soft shot (Rockwell C 39). Chilled iron shot (Rockwell C 63) induces −145,000 psi residual stress in the same steel.

Surface rolling done with a wheel produces biaxial compressive stresses at the surface. These stresses are greater and extend to a greater depth the greater the pressure on the wheel.

Machining and Grinding cold work the surface layers of a metal and will produce residual stresses of the same type as produced by shot peening and other surface working processes. The stresses are usually compressive, confined to a few thousandths of an inch from the surface. The stresses are biaxial, the principal stresses lying parallel and perpendicular to the cutting or grinding direction. The former principal stress is larger than the latter. The magnitude of the stress and thickness of the stressed layer are larger the deeper the cut, the duller the tool or wheel, and the harder the wheel.

Although their effect is believed to be secondary, coolants and lubricants can affect residual grinding stresses, probably because temperature influences the yield strength of the metal.

Grinding or machining stresses depend on the composition of a steel and its heat treatment. For example, the depth of penetration of grinding stresses increases progressively in a manganese oil-hardening tool steel quenched and tempered to Rockwell C 47, in the same steel in an annealed condition, and in an annealed mild steel. When grinding is done correctly with a sharp wheel and adequate coolant, the stresses are generally compressive. When conditions are unfavorable, however, residual tension causes grinding checks.

Rolling can produce residual stresses in metals in many ways. Surface rolling where the metal is not deformed throughout its thickness is discussed with peening, above, but where pressure is exerted over the entire width of the strip, and where rolling proceeds in one direction only, the residual compressive stresses are not biaxial. They lie in the rolling direction only. True flat strip rolling produces uniaxial stress patterns of the kind shown in Fig. 12. The magnitude of the stress at the surface depends on the rolling variables (Fig. 13) in such a way that the last pass given a strip determines the pattern. Thus, a final skin pass can introduce high residual stresses on the strip despite the fact that the strip had been rolled previously in a way that produced low residual stresses.

A third group of residual stress patterns are developed when reductions in thickness are not constant across the width of the strip (as results from springing of the rolls). When reductions are greatest in the middle of the width, stresses will be in the rolling direction and compressive. They will run in the rolling direction along the edges, but will be tensile. Heavier reductions

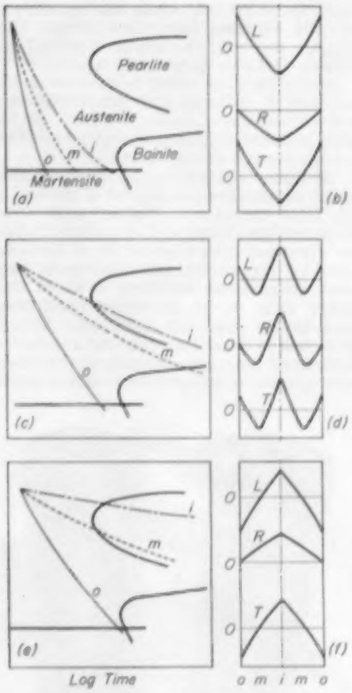

Fig. 8. A Typical Isothermal Transformation Diagram for the Decomposition of Austenite in Steel. A volume expansion occurs when austenite transforms to pearlite, bainite or martensite. If the quenching of a round bar occurs so that the outside fibers cool according to line "o", the middle fibers according to line "m", and the inner fibers according to line "i" as in 8(a), then the residual stress pattern of 8(b) results; if the quenching follows the history of 8(c), the pattern in 8(d) results. Alloying can change the location of the areas marked "pearlite", "bainite", and "martensite", and the cooling lines "o", "m", "i", can be varied, so any of the patterns shown here (and others) may be produced on quenching.

along the edges reverse this pattern.

Wire Drawing produces residual stress patterns of the type given in Fig. 15 when deformation is light (less than 3 or 4% reduction in area) and confined to the surface; or of the type given in Fig. 15 (c) when deformation is penetrating. The magnitude of the stress at the surface depends on the drawing variables as shown in Fig. 16.

Tube Sinking. The stress pattern for tube sinking is shown in Fig. 17. The magnitude of the stress at the tube surface as a function of tube-sinking variables is given in Fig. 18.

Cupping gives the same stress pattern as sinking (except near the bottom of the cup side-wall where, depending on punch and die contours, different patterns can be developed). The amount of working varies from bottom to top of the cup wall, as does the intensity of the stress.

Tube Drawing. In tube drawing, ironing of the wall reduces the stress pattern induced by tube sinking, which usually occurs as the tube first enters the tube-drawing die (Fig. 19).

Electroplating. Residual stresses are found in electroplated coatings. Because lead, cadmium, tin and zinc creep sufficiently at room temperature to relieve stress in general, plates made of these metals do not harbor significant residual stresses. Copper, nickel or chromium plates, on the other hand, develop high residual stresses. Stresses may be either tensile or compressive (−5,000 psi to +15,000 psi in copper from cyanide baths, −10,000 psi to +65,000 psi in nickel from chloride-sulfate baths) depending on bath composition (including pH, impurities and addition agents), bath temperature, current density and plate thickness. Figure 20 shows how iron contamination in a chloride-sulfate bath affects the residual stresses of a nickel plate.

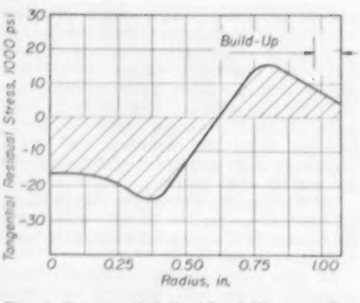

Fig. 9. Tangential Residual Stresses Developed in a 2-In. Shaft of 1040 Steel Built Up 0.040 In. from a 2-In. Diam with Unalloyed Electrodes. The same pattern results whether metal is laid down along or around the shaft. The stress at the surface increases slightly with thicker deposits and can decrease on very thin shafts. (H. Buhler, 1954)

Effects of Residual Stress

Warping. Cutting into a metal that has residual stresses will cause it to deform. There is nothing any more mysterious in this reaction than the popping up of a jack-in-the-box when it is opened. In both instances an impounded stress is unleashed and elastic deformation results. Machining the skin off cold drawn or quenched bars (as in cutting screw threads, milling slots or keyways, or simply machining a shaft to closer tolerances) will cause "snaking", especially where the amount of skin machined off is not symmetrical about the axis. When strip has been unevenly reduced in thickness, slitting across its width will produce cambered narrow strip. Warping can cause secondary effects. A hole drilled into a metal may close slightly as a result of the release of residual stresses; drills and reamers snap off because of the consequent binding, and the metal is blamed for poor machinability!

Breaking of Metals When Cut. When a metal is parted, the pattern of residual stresses is changed throughout the rest of the body. That change may be so great as to raise the stress above the fracture strength of the body at some point, and failure will result. An example, familiar to those who can recall their high school physics demonstrations, is Prince Rupert drops—those glass teardrops loaded with residual stresses that explode when their tips are snapped off with a pair of pliers.

Milling the notch into Charpy bars of high-strength brittle steels often opens a split in advance of the notch. The original residual stress pattern and the changes in it wrought by the milling of the notch lead to the breaking, as given in Fig. 21.

Breaking of Metals Because of Stress Relaxation. The changes in residual stress pattern that lead to fracture, as described heretofore, can be brought about by agencies other than mechanical parting. The milling of the notch in the Charpy bar is not the *immediate* cause of the crack shown in Fig. 21. The immediate cause was the removal of the stress over the portion of the width occupied by the notch *AB* as shown in Fig. 21(*a*). This caused the remaining residual stress pattern to change. The bar would have cracked just as readily if the stress over *AB* had been removed by stress relaxation. Metals are inhomogeneous structures and stress relaxation proceeds at some points more rapidly than at others—along grain boundaries, near some inclusions or voids—and stress relaxation here may shift stress pattern so as to break the metal elsewhere.

Since stress relaxation causes the break, fracture will occur only after a time interval. Examples of such failures include the fracturing of a projectile tip some time after it has passed through armor plate; the cracking of a thick-walled steel tube on a radial plane at the bore some time after be-

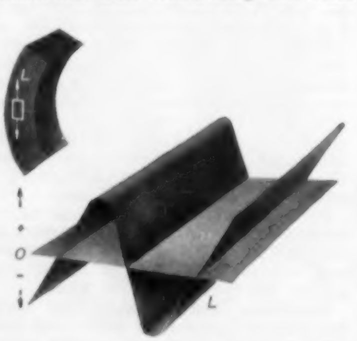

Fig. 10. Residual Stresses Developed on Plastic Bending. The upper left-hand sketch shows the direction in which the bar is bent plastically. Longitudinal residual stresses, L, operate as shown by the arrows. The foreground drawing is a chart of the distribution of these longitudinal residual stresses. Note that the side that was stretched plastically is left in compression and vice versa.

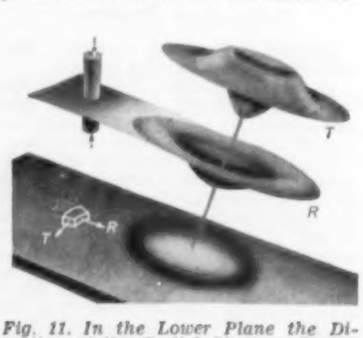

Fig. 11. In the Lower Plane the Direction of the Radial Stresses, R, and Tangential Stresses, T, Is Given. Their distribution in a sheet compressed locally is shown in the two charts above. Both are equal and compressive at the center of the compression. Radial stresses decrease smoothly from this value to zero stress at great distances from the compression, tangential stresses become tensile and diminish to zero at great distances from the center.

ing released from external pressure; the delayed explosion of steel ball bearings upon removal from a tumbling barrel; the spontaneous cracking of quenched and tempered steel helmets weeks after being hit by test bullets; the spontaneous disintegration of projectiles after heat treatment. H. M. Howe wrote in 1920: "In the early days of making armor-piercing shells, spontaneous and violent aging rupture was so common that the shells, after hardening, used to be stored for a considerable length of time in a room to which nobody was admitted."

Breaking of Metals in the Presence of Liquid Metals. Liquid metals can crack solid metals that are residually stressed. Figure 22 shows the relation between stress and the time to fracture for cartridge brass exposed to mercury. The important point here is that without stress—indeed below a critical stress—cracking never occurs. Thus, for example, properly stress-relieved cast iron pots will hold liquid solder or tin for years without failure, though they will fail in 24 hr if not stress relieved. Similarly aluminum solder will crack aluminum alloys if they contain residual stresses.

Fire-Cracking. Metals sometimes crack when heated rapidly. Several factors may be involved. Heating speeds up stress relaxation, and this can cause cracking, as mentioned before. Thus the projectiles that cracked after passing through armor plate did so with greater frequency when put into boiling water than when held at room temperature. They remained unbroken indefinitely when kept in ice water. Heating will also melt low-melting immiscible constituents in an alloy, and this introduces failure as a result of liquid metal attack. Thus, residually stressed, lead-bearing brasses are more susceptible to fire-cracking than lead-free alloys.

Stress-Precipitation Cracking. Alloys that lay down a precipitate more voluminous than the matrix throw the matrix into tension. Cracking can run through such metals when they are aged (see page 89).

Residual Stresses and Fatigue. The relationship between fatigue and residual stresses is controversial. In many instances fatigue life is increased when compressive residual stresses are put into a metal where the fatigue crack would normally start (Fig. 23). There are those who oppose drawing from these data a simple cause-and-effect connection between fatigue life and residual stresses, on the grounds that the methods used to introduce residual stresses also introduce other effects that may be the immediate cause for increasing fatigue life; for example, while inducing compressive residual stresses on the surface of a metal, shot peening also cold works the surface, thereby raising the tensile strength and related fatigue strength. Definitive work is still needed here, but the weight of currently available evidence favors a direct relationship: specifically, compressive residual stresses delay fatigue failures, and tensile stresses hasten fatigue failures.

Typical of the evidence in this direction is the example shown in Fig. 24—a fatigue crack developing in a ball bearing where tensile stresses predominate. Shafts and axles straightened by bending plastically by three-point beam loading are notoriously poor performers where fatigue is concerned. The fatigue failure usually begins next to the load point on the compressed side of the beam. The residual stresses on this side are tensile (Fig. 10).

Relief of Residual Stresses

From the preceding section it is obvious that residual stress patterns in general are deleterious where warping is a problem and that regions of residual tensile stress can be dangerous where certain forms of breaking are to be considered.

General relief and diminution of residual stresses can be obtained by heat-

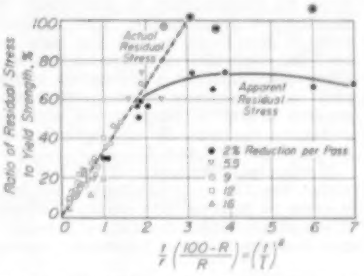

Fig. 13. Effect of Roll Diameter, Strip Thickness, and Reduction in Thickness on Magnitude of Longitudinal Residual Stress at Surface of Rolled Strip of 444 Bronze Strip. (R. M. Baker, R. E. Ricksecker and W. M. Baldwin, Jr., 1948)

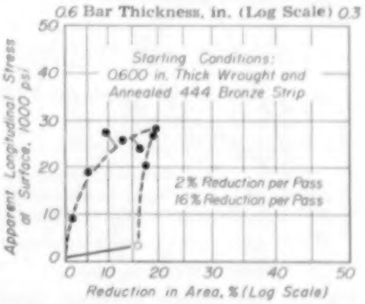

Fig. 14. Longitudinal Residual Stress at the Surface of Rolled Strip as a Function of Rolling Schedule. Roll radius was 13 in. (R. M. Baker, R. E. Ricksecker and W. M. Baldwin, Jr., 1948)

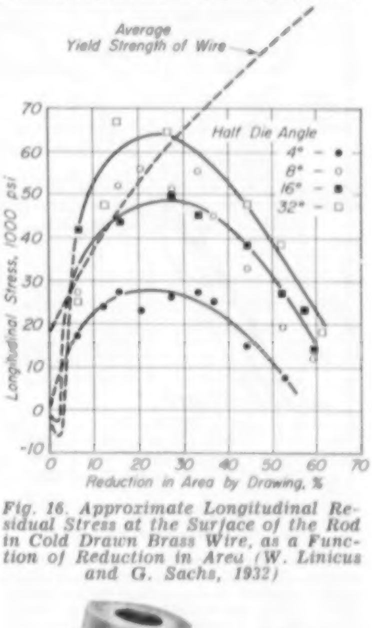

Fig. 16. Approximate Longitudinal Residual Stress at the Surface of the Rod in Cold Drawn Brass Wire, as a Function of Reduction in Area (W. Linicus and G. Sachs, 1932)

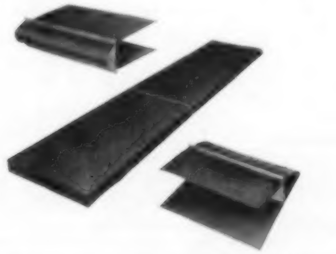

Fig. 12. Two Types of Residual Stress Patterns That Exist in Rolled Strip. Residual stresses lying in the rolling direction will vary over any cross section of the strip. In the upper illustration the longitudinal stresses are compressive at the rolled surfaces (points on the three-dimensional chart behind the reference cross-sectional plane represent compression) and tensile in the interior of the metal. In the lower illustration the longitudinal stresses are tensile at the rolled surfaces and compressive in the interior of the metal.

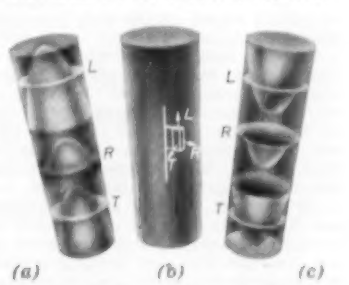

Fig. 15. Two Types of Residual Stress Patterns Found in Drawn Wire or Rod. (b) Defines the directions in which longitudinal stresses, L, tangential stresses, T, and radial stresses, R, operate. In (a) and (c) three-dimensional charts illustrate how each of these stresses varies from point to point over a cross section of the rod. In (a), for example, the graph shows the longitudinal stresses at the surface of the rod to be severely compressive (compressive stresses are indicated by points below the reference cross section) rising to highly tensile values at the rod axis (tensile stresses are indicated by points above the reference cross section).

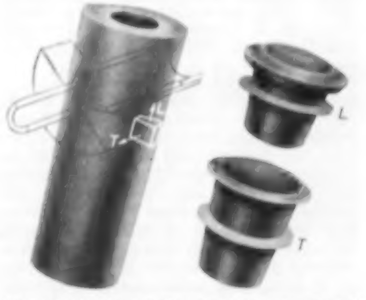

Fig. 17. Residual Stress Patterns Found in Sunk Tube. The sinking operation is illustrated in section in the background. A small element is shown in the tube which serves to define the longitudinal stresses, L, and the tangential stresses, T. The distribution of these is shown at the right where points above the reference planes represent tension and points below represent compression.

ing the metals. The residual stresses become eliminated in two ways, thus:

Heating decreases the yield strength of the metal so that residual stresses deform the warm metal plastically and are thereby relieved. Stress relief by this method is immediate on heating but is limited in degree. The stresses can never be cut below the yield strength of the metal at the temperature used. Such relief of stresses is sometimes deleterious, however. The plastic deformation that relieves the stresses is a form of warping that may be serious in parts requiring close dimensional control. Plastic deformation can also cause fracture, as noted in the paragraph "Fire-Cracking".

Second, residual stresses theoretically will relax or die out at any temperature if given enough time. It should be remembered, however, that the creep of ferrous metals at room temperature is probably measured in terms of hundreds or thousands of years. Thus storing of castings for several months will not stress relieve them. The ineffectiveness of this is discussed on page 33, Table XXV of this Supplement. Heating accelerates this tendency and brings the time for stress relief within reasonable production times. In contrast with the first method of stress relief by heating, stress relief by this method is not limited to any temperature, but neither is it immediate in effect. Parts that might crack if heated suddenly (fire-cracking) can frequently be stress relieved without trouble if heated slowly. It should be remembered that heat and time can anneal a metal in the normal sense—that is, soften the metal and eliminate the effects of cold work.

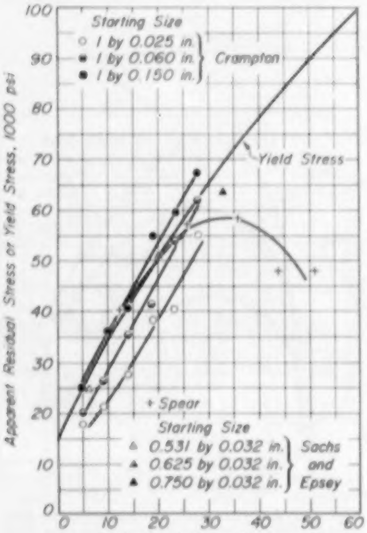

Fig. 18. Approximate Residual Hoop Stress at Outer Surface of Sunk Tube as a Function of Reduction in Diameter. Reductions were effected in a single pass. (D. K. Crampton, 1930; G. Sachs and G. Espey, 1942; R. E. Spear, 1955)

The production man is frequently interested in knowing whether annealing the residual stresses out of his metal will take so much time or such high temperature that he will lose the cold worked temper of the metal, too. In some metals (for example, brass) he may relieve stresses without softening. In other metals (for instance, steels) some overlapping occurs and he must compromise; either he must take some softening to get complete stress relief, or he must be satisfied with partial stress relief to avoid softening.

Table I lists temperatures and times commonly used in the stress relieving of metals and alloys. Times shorter than those given afford less relief; longer times may bring on softening. Higher or lower temperatures than those given may be used, provided the time at temperature is shortened or lengthened accordingly. The general rule of thumb is to cut the time in half for each 10 F increase in temperature contemplated, or to double it for each 10 F decrease contemplated. Instances of partial stress relief without softening (as in steels) are indicated by parentheses in Table I.

Mechanical Methods. It is not always possible to eliminate residual stresses by heating. For example, where stress precipitation cracking is a factor, any attempt to stress relieve the metal thermally brings on the very precipitation that causes cracking.

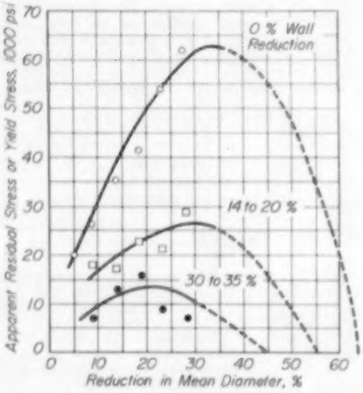

Fig. 19. Approximate Residual Hoop Stresses at Outer Wall Surface of Drawn High Brass Tube. Reductions were made in a single pass. (D. K. Crampton, 1930)

In other instances mere reduction of stress does not give the maximum benefits. Tensile residual stresses may be detrimental to fatigue life; relief of them may increase fatigue life; but substituting compressive residual stresses for tensile stresses will double the benefits gained by mere relief. For these reasons, residual stress patterns are frequently relieved or changed by mechanical working methods based on the principle that any working process will superimpose its distinctive residual stress pattern on any that already exists in the metal.

Stretching a metal only slightly, but enough to put it into the plastic state, reduces any residual stresses (Fig. 25).

Rolling, shot blasting, peening, and other surface working processes are used to induce compressive residual stresses at surfaces subjected to high fatigue stresses or stress corrosion.

These methods must be used judiciously, however. Stress precipitation cracking that occurs in drawn rods can be prevented if the residual stress pattern from drawing (Fig. 15) is added to that resulting from surface rolling (Fig. 12). Since the two patterns are opposite in shape they can be combined so that residual stresses are virtually canceled. On the other hand, experience shows that too light a surface rolling will cancel only those residual tensile stresses near the surface which have resulted from the rod drawing, but will fail to eradicate deeper residual stresses. Cracking can still occur below the surface, where it is far more insidious because it escapes superficial inspection but can still play havoc in subsequent machining operations or fatigue performance.

Measurement of Residual Stresses

The main appeal of qualitative tests for residual stresses is that they are fast, simple, and inexpensive, relying on the principle of stress-corrosion cracking. The metal is submerged in a reagent that will cause stress corrosion. If stresses greater than the critical value are present, the test specimen will crack—sometimes with explosive

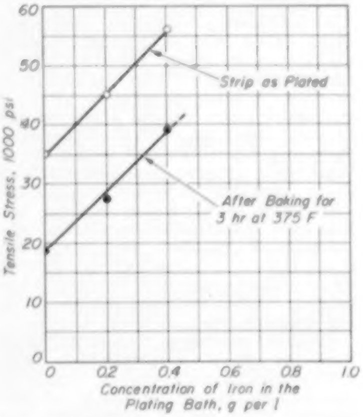

Fig. 20. Increase of Residual Stress in Nickel Plate as a Result of Iron Contamination in Chloride-Sulfate Bath (H. J. Noble, 1955)

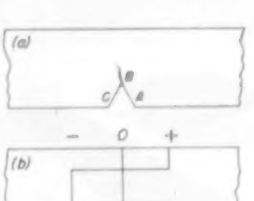

Fig. 21. (a) Crack Frequently Found at Root of Notch Milled in Brittle Steels Having Residual Stresses. (b) A residual stress in the original blank causes cracking when the notch is milled. (c) Removal of metal at bottom of blank removes a tensile force. Remaining stress pattern changes from dashed lines to solid lines and sends stress over fracture stress at root of notch.

violence. The tests are sensitive to surface preparation, reagent cleanliness, and other important details. The oldest and most reliable test of this type is the immersion of brasses in mercurous nitrate solution (ASTM B154). Others include potassium chromate solution for magnesium, boiling sodium nitrate solution for stainless steels, ferric chloride solution for gold and silver alloys, hydrochloric acid for ferritic steels, and sodium hydroxide solution for aluminum alloys. Because of the specific relations between solution and metal in stress-corrosion cracking these tests must be carefully standardized.

Quantitative and semiquantitative tests in which actual values of residual stresses are obtained are with two exceptions based on parting the metal mechanically in a regular and controlled manner and noting the resulting deformation. Frequently these deformations are small so that temperature of the test specimen must be controlled carefully. Furthermore, parting methods should not in themselves introduce or relieve residual stresses; that is, tool forces should not be so heavy as to leave their own residual stress pattern in the piece. The more common methods, the formulas used, and some of the precautions that should be observed in their use are illustrated in Fig. 26 to 37 and are discussed hereafter.

* * *

Johnson's Method (Fig. 26). Longitudinal filaments are cut from the body. Their lengths before and after sectioning (L_o and L respectively) are measured. The stress in the direction of the filament s_t is given by

$$s_t = E\left(\frac{L - L_o}{L_o}\right)$$

where E is Young's Modulus. If the effects of the transverse stresses are neglected, the stress in the direction of the filament may be in error by as much as 30%. The technique is well suited to irregular shapes (rails, for example).

Crampton's Method. A tube is split on a radial plane (Fig. 27). The thickness of the tube, t, and the diameter before and after splitting (D_o and D, respectively) are measured. The hoop stress at the outer (or inner) surface is given by

$$s_t = \frac{E}{1 - \nu^2}\, t \left(\frac{1}{D_o} - \frac{1}{D}\right)$$

where ν is Poisson's ratio.

This equation assumes that the stresses vary from a maximum absolute value at the outer surface to a maximum absolute value at the inner surface according to a straight line. This may be wholly untrue. The tube should be at least twice as long as its diameter to obtain reliable results.

Anderson and Fahlman Method. A tongue is milled from the tube (Fig. 28). The thickness of the tube, t, the length of the tongue, l, and the distance between the tip of the tongue and tube wall, f, are measured. The longitudinal residual stress at the outer tube wall is given by

$$s_t = \frac{E}{1 - \nu^2}\left(\frac{tf}{l^2}\right)$$

This equation is based on the same assump-

Table I. Typical Stress-Relief Treatments

Metal	Temperature,[a] deg Fahr	Time at Temperature,[b] hr
Gray cast iron	800 to 1100	5 to ½
Carbon Steel		
Less than 0.35% C, less than ¾ in.	Stress relief usually not required[c]	
Less than 0.35% C, ¾ in. or greater	(1100 to 1250)	1
More than 0.35% C, less than ½ in.	Stress relief usually not required[c]	
More than 0.35% C, ½ in. or greater	(1100 to 1250)	1
Specially killed for service at low temperature	(1100 to 1250)	1
Carbon-Molybdenum Steel (all thicknesses)		
Less than 0.20% C	(1100 to 1250)	2
0.20 to 0.35% C	(1250 to 1400)	3 to 2
Chromium-Molybdenum Steel (all thicknesses)		
2% Cr, 0.5% Mo	1325 to 1375	2
2.25% Cr, 1% Mo and 5% Cr, 0.5% Mo	1350 to 1400	3
9% Cr, 1% Mo	1375 to 1425	3
Chromium Stainless Steel (all thicknesses)		
Types 410 and 430	(1425 to 1475)	2
Type 405	Stress relief usually not required for thicknesses less than ¾ in.[c]	
Chromium-Nickel Stainless Steel[d]		
Types 304, 321 and 347	Stress relief usually not required for thicknesses less than ¾ in.[c]	
Type 316, more than ¾ in	1500	2
Types 309 and 310, more than ¾ in	1600	2
Welding Dissimilar Materials[d]		
Cr-Mo steel to carbon steel or to C-Mo steel	1350 to 1400	3
Types 410 and 430 to any other steel	1350 to 1400	3
Cr-Ni stainless steel to any other steel	As required for the steel to which Cr-Ni stainless steel is joined	
Copper Alloys		
Copper	300	½
90 Cu - 10 Zn	400	1
80 Cu - 20 Zn, 70 Cu - 30 Zn	500	1
63 Cu - 37 Zn	475	1
60 Cu - 40 Zn	375	½
70 Cu - 29 Zn - 1 Sn	575	1
85 Cu - 15 Ni, 70 Cu - 30 Ni	475	1
64 Cu - 18 Zn - 18 Ni	475	1
95 Cu - 5 Sn, 90 Cu - 10 Sn	375	1
Magnesium Alloys		
M-1, hard rolled sheet, 1.5 Mn	400	1
M-1 extrusions, 1.5 Mn	500	¼
AZ31X hard rolled sheet, 3 Al, 1 Zn, 0.3 Mn	300	1
AZ31X extrusions, 3 Al, 1 Zn, 0.3 Mn	500	¼
AZ51X hard rolled sheet, 5 Al, 1 Zn, 0.25 Mn	375	1
AZ61X extrusions, 6 Al, 1 Zn, 0.25 Mn	500	¼
AZ80X extrusions, 8.5 Al, 0.5 Zn, 0.15 Mn	400	1
AZ80X HTA extrusions, 8.5 Al, 0.5 Zn, 0.15 Mn	600	¼
Nickel Alloys		
Nickel and Monel	525 to 600	3 to 1
"K" Monel and "KR" Monel	525 to 600	3 to 1
80 Ni - 20 Cr, Inconel, 60 Ni - 25 Fe - 15 Cr	700 to 900	3 to 1

(a) Temperatures in parentheses give partial relief of stresses. (b) The interval during which the entire piece is at temperature. (c) Unless necessary in order to obtain dimensional stability. (d) Rate of heating should be less than 200 F per hr. For the other ferrous metals a heating rate of less than 400 F per hr is recommended. All ferrous metals should be cooled from the stress-relieving temperature at a rate not greater than 200 F per hr.

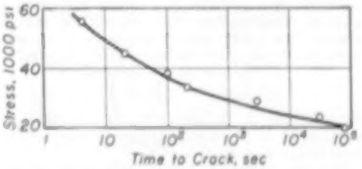

Fig. 22. Cracking Time for a Stressed Cartridge Brass Immersed in Mercurous Nitrate (H. P. Croft, 1941)

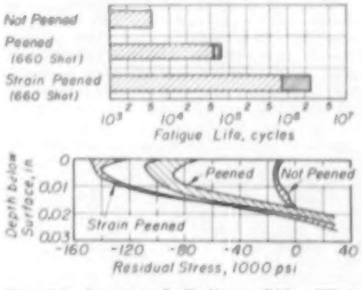

Fig. 23. Increased Fatigue Life (Unidirectional Stress Between Zero and 200,000 Psi Tension) in Peened, Heat Treated 5147 Steel

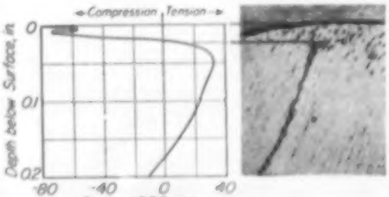

Fig. 24. Residual Stresses in a 13/16-In. Ball Bearing Made of 52100 Steel Normalized at 1635 F, Air Cooled, Austenitized at 1440 F, Water Quenched and Tempered at 250 F for ½ Hr Are Shown at Left. Fatigue crack developing in tensile region is shown at right. Note how crack veers parallel to ball-bearing surface when it reaches the compressively stressed surface layer. The surface eventually spalls off.

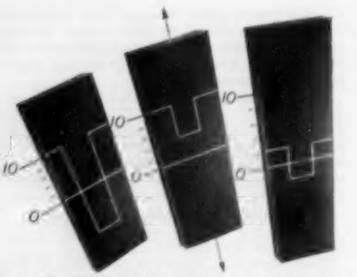

Fig. 25. The Action of Stretching on Residual Stresses Operating in the Direction of Stretching. Original residual stress state is shown at left. Stretching the bar carries the metal into the plastic state in the outer edges as shown in the middle, so that on relief of the stretching, residual stresses are reduced as at the right.

tion as Crampton's and is liable to the same error. Best results are obtained when the tongue width is 10 to 15% of the tube diameter.

Anderson and Fahlman Method (Applied to Sheet). A sheet is split on its central plane (Fig. 29). The total sheet thickness, t, the length of the cut, l, and the gap opening, f (the distance from tip of one curled back half to the other), are measured. The longitudinal stress s_l at the strip surface is given by

$$s_l = \frac{E}{1-\nu^2}\left(\frac{tf}{l^2}\right)$$

This equation is based on the same assumption as Crampton's and is subject to the same error.

Kreitz' Method. This is the same as Anderson and Fahlman's method applied to rods. The rod is first cut into a slab and then split as shown in Fig. 30. The formula is the same as in the Anderson-Fahlman method applied to strip.

Treuting-Read Method. A succession of layers are etched off one side of sheet (Fig. 31). The radii of curvature in two directions, r_x and r_y, and the sheet thickness, t, are measured as each layer is removed. From these, two parameters are calculated

$$P_x = \frac{1}{r_x} + \frac{\nu}{r_y} \text{ and } P_y = \frac{1}{r_y} + \frac{\nu}{r_x}$$

and plotted against the sheet thickness. The slope of these curves dP_x/dt and dP_y/dt at a given value of t, the area under these curves from $t = t_0$ (the original thickness) to the given value of t,

$$\int_{t_0}^{t} P_x dt$$

and the values of P_x and P_y at this value of t are substituted in this formula to obtain the values of the residual stresses s_x or s_y at the value of t:

$$s_x = -\frac{E}{6(1-\nu^2)}\left[(t_0+t)^2\frac{dP_x}{dt} + 4(t_0+t)P_x + 2\int_{t_0}^{t} P_x dt\right]$$

$$s_y = -\frac{E}{6(1-\nu^2)}\left[(t_0+t)^2\frac{dP_y}{dt} + 4(t_0+t)P_y + 2\int_{t_0}^{t} P_y dt\right]$$

The stresses determined by these equations are true.

Siebel and Pfender Method. Blocks in two directions perpendicular to each other are cut out of a sheet as shown in Fig. 32. The lengths between two gage marks in these blocks are measured before and after sectioning, l^o_x and l_x respectively, for one block, and l^o_y and l_y for the other.

These measurements are converted to strains according to

$$\varepsilon_x = \frac{l_x - l^o_x}{l^o_x} \qquad \varepsilon_y = \frac{l_y - l^o_y}{l^o_y}$$

The stresses operating in the direction of the lengths of these two blocks are given by

$$s_x = \frac{E}{1-\nu^2}(\varepsilon_x - \nu\varepsilon_y)$$

$$s_y = \frac{E}{1-\nu^2}(\varepsilon_y - \nu\varepsilon_x)$$

These equations assume that the stress in the sheet is the same throughout the sheet thickness.

Mathar's Method. A hole is drilled out of a sheet or into a thick chunk of metal (Fig. 33). Strain gages having been placed radially around the hole before it was drilled, the strains in three different directions are read off. When the gages are placed 120 deg from one another, the formulas for the stresses at the surface of the sheet are

$$s_p = E\left(\frac{A}{1-\nu} + \frac{B}{1+\nu}\right)$$

$$s_q = E\left(\frac{A}{1-\nu} - \frac{B}{1-\nu}\right)$$

Here s_p and s_q are the principal stresses and

$$A = \tfrac{1}{3}(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)$$

$$B = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_1-\varepsilon_2)^2 + (\varepsilon_1-\varepsilon_3)^2 + (\varepsilon_2-\varepsilon_3)^2}$$

where ε_1, ε_2, and ε_3 are the three measured strains.

Four-Shot X-Ray Method. An x-ray beam is directed at the surface of a metal from four different directions successively (Fig. 34). Most conveniently these directions are: one shot normal to the surface, the other three shots at 45 deg to the surface and with their projections on the surface 60 deg from one another. The lattice parameter is calculated from those diffraction rings that are as close to a 90-deg diffraction angle as possible, for all four shots; d_1 is the parameter figured from the perpendicular shot; d_2, d_3, d_4 are the parameters from the other three shots. The stress lying in the surface of the metal and in the direction of the projection of the three inclined shots is given by

$$s_i = \frac{E}{2(1+\nu)}\left(\frac{d_i - d_1}{d_1}\right) \qquad i = 2, 3, 4$$

for the angles mentioned above.

The principal stresses in terms of these stresses (assuming shots 2, 3, and 4 are made at 60-deg jumps) are

$$s_1 = \frac{1}{3}\left[s_2+s_3+s_4+\sqrt{(s_2-s_3-s_4)^2+3(s_3-s_4)^2}\right]$$

$$s_2 = \frac{1}{3}\left[s_2+s_3+s_4-\sqrt{(s_2-s_3-s_4)^2+3(s_3-s_4)^2}\right]$$

$$\tan\phi = \frac{\sqrt{3}(s_3-s_4)}{2s_2-s_3-s_4}$$

where ϕ is the angle between the projection of the third shot and the first principal stress.

A short-cut procedure is the two-shot method. In determining biaxial stresses, one shot is made normal to the surface and another shot at 45 deg to the surface. The specimen is then rotated 90 deg, and the procedure is repeated. By this method, the spacing of the diffraction rings is related to the tangential and longitudinal stresses existing in the piece.

Heyn and Bauer's Method. Successive layers are machined or pickled off a rod (Fig. 35). The length, l, and diameter, d, are measured at each removal. The product $\varepsilon_l a$ (where ε_l is the longitudinal strain $(l - l_0)/l_0$ and a is the cross-sectional area of the rod calculated from $\pi d^2/4$) is plotted as a function of a. The slope of this curve $d(\varepsilon a)/da$ at a given radius is substituted in the formula

$$s_l = E\left(\frac{d\varepsilon a}{da}\right)$$

to obtain the longitudinal residual stress, s_l, at the radius in question. The neglect of the transverse stresses in this formula makes the value of the longitudinal stress only an approximation. The true stress may be as much as 30% different from this value.

Mesnager-Sachs Method. A hole is bored out of a rod (or tube) at successively larger radii (Fig. 36). The length of the rod, l, and its outside and inside diameters D^o and D^i, respectively, are measured after each removal. The longitudinal ε_l and tangential ε_t strains are formed as follows

$$\varepsilon_l = \frac{l - l_0}{l_0} \text{ and } \varepsilon_t = \frac{D^o - D^o_0}{D^o_0}$$

where the subscript "o" indicates the original value of the length or diameter before boring. These strains are assembled into the parameters

$$\lambda = \varepsilon_l + \nu\varepsilon_t \text{ and } \theta = \varepsilon_t + \nu\varepsilon_l$$

These parameters multiplied by the area of the remaining tube are plotted as a function of the area of the remainder of the rod, a. The slopes of these curves, $d(a\lambda)/da$ and $d(a\theta)/da$, at a given diameter of the rod, yield the longitudinal, tangential, and radial residual stresses, s_l, s_t, and s_r, respectively, at that diameter, according to the formulas:

$$s_l = \frac{E}{1-\nu^2}\left(\frac{d(a\lambda)}{da} - \lambda\right)$$

$$s_t = \frac{E}{1-\nu^2}\left(\frac{d(a\theta)}{da} - \theta\right) - s_r$$

$$s_r = \frac{E}{1-\nu^2}\left(\frac{a\theta}{2(a_0 - a)}\right)$$

Alternate Mesnager-Sachs Method. A hole is bored out of a rod; then successive layers are machined off the outside of the rod (Fig. 37). The rod length, l, and inside and outside diameters are measured after each removal. The mode of calculating the stresses is the same as in the preceding method.

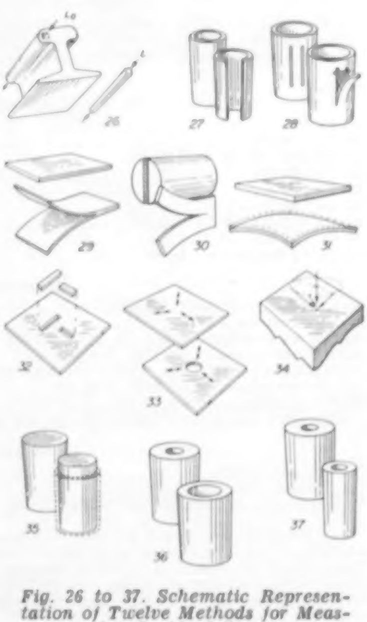

Fig. 26 to 37. Schematic Representation of Twelve Methods for Measuring Residual Stresses

The Selection of Electroplated Coatings

By the ASM Committee on Electroplated Coatings

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AMONG THE METHODS for applying metallic coatings (electroplating, cladding, metal spraying, vacuum evaporation, chemical reduction, displacement, and hot dipping) electroplating is the most widely used.

The primary purpose of electroplated coatings is twofold: to protect against corrosion and to enhance the appearance of the common metals, which, although satisfying the requirements of availability, cost and mechanical properties, are attacked by moist atmospheres and by various liquids that come into contact with them. Other purposes for electrodeposits include resistance to wear and abrasion, improvement of surface electrical conductivity, rebuilding of worn parts and other uses as discussed in the last part of this article.

Corrosion attack may be severe, as that experienced by steel in marine atmospheres; or mild, as that which discolors brass indoors. The attack on the basis metal can be prevented or mitigated by electroplates that either envelop the susceptible surface completely or inhibit the corrosive action electrochemically. In addition to preventing corrosive attack, the protective film may be required to withstand wear or abrasion, or it may be expected to impart sales appeal to an otherwise unattractive article.

The information in this article is divided into two principal sections: Protective and Protective-Decorative Coatings, and Special-Purpose Electroplates. These sections are subdivided according to the metals commonly used as coatings, and examples of applications for each coating are given with an indication of the factors that determine the selection.

General Considerations

In selection of suitable electrodeposits, adequate information is needed concerning several factors:

Service Performance of different coating metals is usually the most important factor and will be determined by considerations such as: nature of environment; whether protection is anodic (sacrificial) or by envelopment, and whether abrasion will be encountered. Performance data will usually indicate the coating metal and the thickness necessary to meet requirements for length of service expected.

Appearance. The luster and its permanence are sometimes more important than protective properties of the deposited metal. The truly decorative finishes, such as chromium, brass, gold and silver, belong in this group. Zinc can be deposited with a lustrous finish, but unless the deposit is lacquered it soon becomes dull after outdoor exposure. Cadmium plate has a bright appearance but is easily stained and finger marked. Recent improvements in the solutions used in bright nickel plating not only permit a bright deposit, but also will level slight polishing imperfections. This may be an important economic factor.

Physical Effects. Hydrogen embrittlement of medium-carbon and high-carbon steels, particularly those under high residual or applied stress, can result from the hydrogen evolved during cleaning, plating and treating in acids. Sometimes the fatigue strength of steel is affected adversely by electrodeposits that involve high tensile stress.

Cost. In electroplating, the metals most commonly used vary greatly in cost but the total cost of finishing does not necessarily vary in the same ratio. The method of deposition, whether by barrel plating or individual suspension of each article, is an important consideration. Racking and masking, if necessary, and the surface preparation that precedes plating are important items of expense.

Supplements the article on pages 716 to 720 of the 1948 ASM Metals Handbook

Influence of Shape

The thickness of an electrodeposited coating varies from projections to depressions, unless elaborate racking or other plating devices are utilized to eliminate or reduce this tendency. Without these modifications, too costly for many applications, the coating is always thicker at projections and thinner in depressions, and varies with the size and shape of the projection or depression. Also, the article should be designed so that all surfaces to be plated can be reached by the cleaning and rinsing as well as the plating solutions. Solutions trapped in pockets and deep recesses contaminate one bath with another as the part moves through the plating cycle, and unsightly defects also result.

Another provision necessary in the design is for the escape of gases that are released during cleaning and plating. If these are trapped in pockets, they force the solution out of the pockets and result in unplated areas. If, because of shape, the part will not conduct the plating current uniformly to all surfaces from a single point of cathode contact, multiple contacts must be provided in the rack design.

The effect of projections and depressions on the uniformity of the coating thicknesses from various baths is exemplified by an open-end box (4-in. cube). The open end of the box was pointed toward one of the anodes to produce the most desirable condition for this shape without auxiliary thieve-rings, shields, bipolar anodes, insoluble anodes or other devices. Results of plating this box in silver (cyanide), copper (cyanide), cadmium (cyanide) and nickel (sulfamate) are shown in Fig. 1. These diagrams illustrate two facts: thickness of plate varies significantly from place to place on the simplest shape; and various plating baths have different throwing power or ability to plate uniformly over the surface, regardless of shape.

The data in Table I show that the silver-plated box was the most uniformly plated, and that even with the most uniformly plated part, the average thickness on the inside bottom of the box was only 20% of that on the outside of the bottom. This table indicates also that in these particular tests, cadmium (cyanide) has more than twice the throwing power of nickel (sulfamate); copper (cyanide) about three times; and silver, four times. Uniform covering of the object is rarely the most important factor. However, the values in Table I may be varied to a limited extent by changing the composition of solution and the operating conditions. Normally, the metals plated from cyanide or alkaline baths will be more uniformly distributed than metals from acid baths.

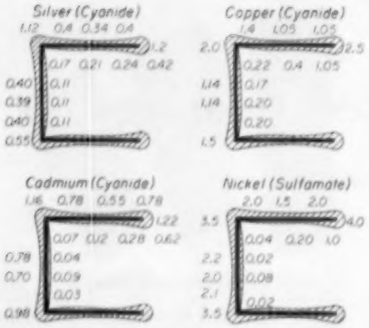

Fig. 1. Cross Sections of Plated Boxes (4-In. Cubes Having Open End Pointed Toward Anode During Plating) Showing Variations in Coating Thickness. Numbers indicate thickness in mils at each location. (Drawing is not to scale.) For thickness ratios see Table I below.

Table I. Effect of Shape of Article and Plating Bath on Coating Distribution

Plating Bath	Ratio on Side(a)	Ratio on Bottom(b)
Ag (cyanide	1: 2.5	1: 5
Cu (cyanide)	1: 3.0	1: 6
Cd (cyanide)	1: 4.25	1:12
Ni (sulfamate)	1:10.0	1:33

(a) For open-end box, 4-in. cube, ratio of average plating thickness on inside to average thickness on outside. (b) Same as (a) for bottom of box.

See Fig. 1 for individual measurements.

Some of the solutions widely used for plating, arranged in the order of least effect of shape on distribution (gold plating) to greatest effect of shape (chromium plating) are approximately as follows: gold, silver, alkaline tin, alkaline copper, alkaline cadmium, alkaline zinc, acid tin, high-pH nickel, acid cadmium, low-pH (ordinary) nickel, acid copper or zinc, iron, and chromium. This order can be altered slightly by changes in bath composition and plating conditions.

Plating into angles is particularly difficult. The plate is thinnest at the junction of two flat surfaces meeting at less than 180 deg. The angle at which the surfaces meet is a factor in determining the ratio of average to minimum plate thickness. This ratio indicates the total amount of plated metal required to provide the necessary protection to the area of minimum thickness. The ideal shape would have no acute angles, and all surfaces would be equidistant from the anodes in the plating tank.

For example, the distribution of the plate on a cylindrical surface would be uniform, assuming best arrangement of anodes; that is, ratio of average to minimum thickness would be 1.00. As nonuniformity of plate thickness increases, this ratio increases. In one particular example, on two surfaces meeting at a recess angle of 120 deg, the ratio was 1.9 for electroplated nickel; on surfaces meeting at 90 deg the ratio was 2.7; and on surfaces meeting at 60 deg the ratio was 3.3. The larger the recess angle at which the plane surfaces meet, the more favorable is the shape for plate distribution.

Recessed areas should be provided with a radius as large as possible. For example, the recessed area at point (a) of Fig. 2 has a ratio of 9; a ¼-in. radius at (b) reduces this ratio to 5.5. Projections from plane surfaces should blend into the plane surface by means of a generous radius; any increase in this radius will decrease the ratio substantially.

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Galvanic Corrosion

When two dissimilar metals are in electrical contact in an electrolyte, galvanic corrosion may occur. This consists of accelerated attack of one metal (anodic or more active) and reduced attack of the other (cathodic or more noble). This type of corrosion may arise in the use of electroplated steel from two sources: (1) at discontinuities in a metal coating a galvanic couple exists between the basis metal and the coating, and (2) a plated part may be used in contact with a different metal.

The extent of galvanic attack depends on many factors. The most important are: (1) the nature of the two metals, (2) the extent of wetting and the conductivity of the wetting liquid, and (3) the relative areas of anode to cathode.

The behavior of different metals in galvanic couples depends on the nature of the service environment. On the basis of tests with a large number of corrosive conditions and metal combinations, some of the common metals and alloys have been arranged in a list called the galvanic series, from the least noble or anodic, magnesium, to the most noble or cathodic, platinum, (Table II).

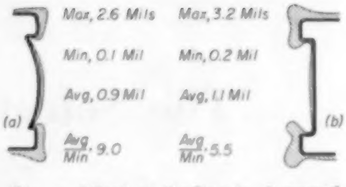

Fig. 2. Effect of Radius in Recessed Area on Thickness of Nickel Plated Coating

The extent and type of wetting is an important factor in determining the severity of galvanic attack. For indoor service where wetting is infrequent, galvanic corrosion is no problem. Outdoors, attack may be relatively rapid in sea coast and industrial environments, where contamination, hence conductivity, of rain and condensed moisture is high.

Several rules apply in choosing a metal combination for use in corrosive environments:

1. Select metals as close together in the series as possible.
2. For the anodic protection of steel, metals above steel in the series should be selected.
3. Avoid combinations having a smaller area of the more anodic metal than of the cathodic or more noble metal. Such combinations result in excessive current density on the anodic areas.
4. Dissimilar metals should be insulated whenever possible to minimize galvanic corrosion.

Typical Applications. Zinc is more active than steel; so at discontinuities in zinc plate, the steel is protected. Nickel, on the other hand, is less active than steel and will normally accelerate the corrosion of steel at discontinuities in nickel plate.

Table II. Galvanic Series of Metals and Alloys

Corroded end
(anodic, or least noble)
Magnesium
Magnesium alloys
Zinc
Aluminum alloy
1100 (2S)
Cadmium
Aluminum alloys
2017 (17S)
2024 (24S)
Steel or iron
Cast iron
Nickel cast iron
Lead-tin solders
Lead
Tin
Brasses
Copper
Bronzes
Copper-nickel alloys
Monel
Silver solder
Nickel
Inconel
Chromium iron
18-8 Stainless
18-8 Mo Stainless
Hastelloy C
Silver
Graphite
Gold
Platinum
Protected end
(cathodic or most noble)

When stainless steel, ordinary steel and brass components are cast into aluminum and magnesium parts, the inserts should be coated with cadmium or zinc to reduce the electropotential difference between the aluminum or magnesium and the inserted components to decrease galvanic corrosion.

If moisture is present, and external corrosion conditions are encountered, it is helpful to insert a zinc chromate primer between the plated parts and the magnesium or aluminum. This type of system affords double protection —electrochemical and direct insulation between contacting surfaces. For applications involving copper or copper alloy parts in contact with steel in environments conducive to galvanic corrosion, both parts should be plated with cadmium to reduce the possibility of galvanic corrosion.

In general, if a metal below steel in the series must be in contact with the steel, and the conditions are favorable for galvanic corrosion, then a coating (such as cadmium) should be used on both metals to lower the electropotential between the parts.

Specifications

The specifications most frequently referred to are those published by the American Society for Testing Materials. Some of these were prepared jointly by ASTM, the American Electroplaters' Society and the National Bureau of Standards. Others are endorsed by AES. These specifications reflect the combined experience of representatives from suppliers of electroplating materials, and manufacturers and purchasers (including government agencies) of electroplated products. Corresponding specifications prepared by individual companies and agencies are usually similar to those of ASTM in requirements, but may be more restrictive in defining properties and testing procedures that are most pertinent to the specific service conditions anticipated for particular products. Requirements commonly specified for coatings such as zinc that are applied only for protection against corrosion include the following:

1 **Thickness** may be specified as an average, but more frequently as a minimum, on any significant surface. Thickness may be determined by: *(a)* microscopic examination of the cross section, *(b)* time required for penetration of the coating by a corrosive solution under standardized conditions, *(c)* magnetic methods, *(d)* complete stripping (to determine average thickness), and *(e)* micrometer measurements before and after plating. Significant surfaces are those that are visible and are subject to corrosion or wear or both, and are commonly defined as any surfaces that can be touched by a ball of given diameter (such as 0.75 in.).

2 **Adherence** is evaluated visually by the extent of flaking and peeling in the as-plated condition or by flaking and peeling of the plating after deformation of the part or test panel.

3 **Surface appearance** is evaluated visually for defects.

4 **Basis metal preparation,** if improper, will result in poor adherence or surface defects.

For coatings that must be decorative as well as protective (nickel-chromium) the following additional characteristics may need to be specified:

5 **Appearance** of the product may be evaluated by comparing it with standards for color, gloss and texture.

6 **Inherent Porosity** may be indicated by rust spots after a salt spray test.

Tables III, IV and V list the thicknesses and salt spray requirements, where applicable, from some ASTM specifications on protective coatings. The coating types are defined by two letters: the first is an arbitrary designation for grade of plating; the second refers to the basis metal—S for steel, Z for zinc, and C for copper and copper alloys. Coatings of types DS and FS of thickness equal to or greater than shown in Table V are frequently specified for severe outdoor exposure on parts such as automobile bumpers.

Salt Spray Testing. Data from salt spray tests generally do not predict or correlate with service performance of electrodeposited metallic coatings. When applied to electrodeposited zinc coatings on steel, the salt spray test is useful only in detecting thin areas. As applied to other electrodeposited coatings, the salt spray test is not reproducible within itself.

Hydrogen Relief Treatment

The embrittlement caused by hydrogen released during chemical and electrochemical processing of cold worked or moderately hardened steels can be alleviated by holding the plated parts in the range from 250 to 400 F for 1 to 3 hr within 15 min of plating. Sometimes a minimum of 3 hr at 375 F is specified. All plated ferritic (or martensitic) steel having a hardness of Rockwell C 34 or higher should receive the hydrogen relief treatment. Before the treatment careful handling during finishing operations is necessary to prevent stressing of the parts.

When high residual or other stresses are present, the treatment should follow immediately. If residual stresses are severe from grinding or thread rolling, it may be necessary to bake the parts *before* plating also.

PROTECTIVE AND PROTECTIVE-DECORATIVE COATINGS

Although an electrodeposited coating may be selected to serve primarily as protection, other factors must often be considered—appearance, effect on fatigue strength, environment in which the part is used, galvanic relationship of the coating to the basis metal, electrical conductivity of the coating and its oxides, mechanical factors of fretting and general wear, natural formation of film, conversion coating possibilities, ease of application and the general economics of the process.

Decorative coatings are judged primarily by their appearance, in many applications without consideration of their protective properties.

Cadmium

Electrodeposits of cadmium are used extensively to prevent corrosion of steel, cast iron, brass and bronze. Because cadmium is anodic to these alloys, they are protected at the expense of the cadmium in contact with them, even though the plated coating becomes scratched or nicked, exposing the basis metal. However, cadmium reacts with water, oxygen and other chemicals in the atmosphere to form insoluble corrosion products, which do not form a continuous film or stop further corrosion (generally called "white rusting") of the electrodeposit. The corrosion of the plate can be inhibited by chromate coating, and often must be, to avoid unsightly appearance and the malfunctioning of certain plated parts.

One reason for preferring cadmium to zinc is that cadmium plating forms a smaller amount of corrosion products than zinc (particularly in marine atmospheres) and retains its initial appearance for a longer time. This is an important consideration in applications where a build-up of corrosion products would have a detrimental effect, such as preventing the flow of current in electrical components or movement of closely fitting parts. For such applications cadmium should be chosen in preference to zinc. Also, cadmium is more solderable. Cadmium is preferable to zinc for plating gray iron and malleable iron castings.

The corrosion of the plating can be retarded by applying a supplemental chemical conversion coating of the chromate type. The chromate films, produced by immersing the plated article in a solution containing chromic acid or other chromates and catalytic agents, provide protection against initial corrosion through the inhibitive properties of the water-soluble chromium compounds present in the films. These chromate-type conversion coatings are excellent as bases for bonding paint or enamel to the cadmium plate. However, the chromate finish must not be applied before the stress-relief heat treatment, or its beneficial effect will be destroyed by the elevated temperature.

Cadmium plate should not be specified on parts that come into contact with food because of the danger of ingestion of cadmium in food or drink, which can result in poisoning.

Table III. Frequently Specified Nickel-Chromium Coatings on Steel for Outdoor Exposure

Minimum Specifications

1.2 mils Cu plus Ni; final thickness of Ni, 0.6 mil after buffing; 0.01 mil Cr if required

Intermediate Specifications

2.0 mils Cu plus Ni; final thickness of Ni, 1.0 mil after buffing; 0.01 mil Cr if required

These coatings correspond to types FS and DS of ASTM A166-55T.

Table IV. Electrodeposited Coatings of Zinc on Steel (ASTM A164-53)

Type of Coating	Minimum Thickness, [a] mil
GS	1.0
LS	0.5
RS	0.15

(a) On surfaces that are visible and subject to wear or corrosion

ASTM B201-55T, on chromated zinc coatings, and ASTM B117-54T give additional information on zinc coatings.

Table V. Thickness Specification for Nickel and Chromium on Steel (ASTM A166-54T)

	Minimum Coating Thickness, mil			
	ASTM Type			
Metal	DS	FS	KS	QS
Cu + Ni	2.0	1.2	0.75	0.4
Final Ni	1.0	0.60	0.40	0.20
Cr (if required)	0.01	0.01	0.01	0.01

The periods of continuous exposure to the salt spray test (ASTM B117-54T) that coatings should withstand without showing appreciable corrosion on significant surfaces is a matter for agreement between supplier and purchaser.

Typical Applications. The minimum thickness specified for cadmium plate is usually between 0.1 and 0.5 mil, depending on service requirements. Threaded fasteners present a special problem, and thicknesses of 0.1 to 0.15 mil are usually specified.

If an electrodeposited coating is to be applied to a highly stressed part, it is important that the processing should not decrease the fatigue strength of the part. The application of some electrodeposited coatings, including cadmium, decreases fatigue strength—largely as a result of hydrogen embrittlement and failure to observe the precautions for baking treatments.

This is particularly important when cadmium is plated on parts heat treated to hardnesses of Rockwell C 34 and higher, for cold worked parts or for shot peened or cold rolled parts such as roll-threaded bolts or studs. It is customary to stress relieve such parts for 1 to 3 hr at 375 F immediately after plating. Carburized parts and other hardened parts that cannot be heated to 375 F should be held at 275 F for 5 hr or longer. This treatment must not be omitted for parts that will be highly stressed in service.

Springs are often electroplated with cadmium to protect them against corrosion and abrasion. Since the basis metal is under various kinds and amounts of stress, imperfections in the surface constitute stress raisers and are potential points of failure. This surface must be protected during fabrication of the spring and during plating. Since it is usually necessary to specify high-carbon steels for springs, to obtain high elastic strength, it is important to control the effects of hydrogen in the cleaning and electroplating processes.

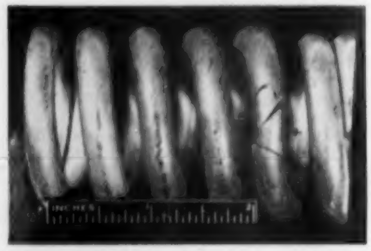

Fig. 3. Failure of Cadmium Plated Spring Caused by Hydrogen Embrittlement during Plating

Acids, even those containing inhibitors, should not be used for descaling or neutralizing unless heating is to follow immediately. Other cleaning procedures for springs must not cause hydrogen to be evolved.

Generally, cadmium coatings are selected for the protection of springs because less hydrogen is evolved during plating than with zinc. Alkaline plating baths are preferred because of their superior throwing power. Electroplated springs must be baked at 350 to 400 F to release occluded or absorbed hydrogen as soon as possible after electroplating, as described previously. Figure 3 is an example of a failure of a cadmium-plated compression spring that was not properly treated to release occluded or absorbed hydrogen. A description of the spring, which was used in a high-temperature relief valve and under intermittent loading is as follows: wire size, 0.343 in.; OD of spring, 2.00 in.; length, 3.00 in.; six coils; 6150 alloy steel at Rockwell C 43; stress relieved immediately after coiling. The plating sequence was:

1. Clean with alkaline solution.
2. Rinse in cold water.
3. Electroplate with cadmium 0.3 mil thick.
4. Rinse in hot water.
5. Relieve hydrogen embrittlement in boiling water ½ hr.

The shatter type of fracture on this spring is typical of that caused by hydrogen embrittlement. The corrective action should have been to bake the spring at a higher temperature and for a longer time.

Another example of a plating requirement on a steel spring is a contact bridge that must be able to resist wear, corrosion and the effects of electrical current. After being cleaned by mechanical means (*acids must not be used*), a composite plate consisting of 0.25 mil Cd and 0.25 mil Sn should be applied, if the design is such that the rubbing parts of the contacts can be masked readily. If not, the whole assembly should be cleaned mechanically, plated and the cadmium-tin finish then ground off the surfaces of the silver contacts. After plating, the assembly should be held 1 hr at 330 to 340 F to remove the hydrogen, provided this temperature will not change the properties of the spring.

Electrodeposits of cadmium 0.5 to 0.75 mil thick are used in the aircraft industry on engines, propellers, airframe and landing gear parts with satisfactory service life. The plate can be applied readily, even to complicated parts, because of the good distribution characteristics of the process.

Zinc

Zinc, like cadmium, is anodic to steel and many nonferrous alloys and therefore offers more complete protection when applied in thin films than similar thicknesses of nickel and other cathodic coatings.

Because it is relatively cheap and readily applied in barrel, tank or continuous plating facilities, zinc is often preferred for coating ferrous parts (Table IV) when protection from atmospheric and indoor corrosion is the primary objective. Normal electroplated zinc without subsequent treatment becomes dull gray in appearance after exposure to air. Bright zinc and a supplementary coat of either a bleached chromate conversion coating or a clear lacquer, or both, is sometimes used as a decorative finish less durable than nickel-chromium but suitable for indoor service. Plating of zinc on gray iron and malleable iron presents serious operational difficulties. Cadmium is usually preferred.

Electroplated zinc is only slightly harder (less than Vickers 100) than lead and tin; hence it will not resist severe abrasion or provide a good wearing surface. It is generally unsatisfactory for bearing surfaces.

The noncorrosive fluxes required in communications equipment are not suitable for soldering to zinc surfaces. For radio and other electronic chassis to which ground connections must be soldered, cadmium or an alloy of tin-zinc is preferred for coating. A second restriction of zinc plate for certain electronic or other communications equipment is a tendency to grow "whiskers" in service. These metal filaments are most troublesome at low voltage (below 10 v) in equipment that is not exposed to direct air currents. Cadmium and tin are also susceptible to whisker growth.

In the presence of moisture zinc becomes a sacrificial protecting agent when in contact with metals below it in the galvanic series (Table II). Attack is most severe when the electrolyte is highly conducting (as in marine atmospheres) and when the area ratio of zinc to the second metal is small. Unprotected zinc-plated screws are not used to fasten bare parts if the service is to include marine exposures. Since zinc is anodic to steel, pores in thin coatings do not affect the basis steel.

The life of a zinc coating in the atmosphere is nearly proportional to the coating thickness. Its rate of corrosion is highest in industrial areas, lowest in rural locations and intermediate in marine environments. The corrosion is greatly increased by frequent dew and fog, particularly if the exposure is such that evaporation is slow.

Table VI gives estimated life of zinc coatings on steel in different outdoor atmospheres. These data cannot be applied literally to every environment but they can be used as a general guide.

Because corrosion is rapid in industrial or marine locations, parts that must endure for many years are usually protected by supplementary coatings. For example, steel with 0.2 mil of electroplated zinc is often painted to obtain a coating system for general outdoor service. A phosphate or chromate pretreatment of the surface insures suitable adherence of the paint to the zinc.

In normal uncontaminated indoor atmospheres, zinc corrodes very little. A 0.2-mil coating has been known to protect steel framework on indoor cabinets for more than 20 yr. Atmospheric contaminants will accelerate corrosion of zinc if condensation occurs on cooler parts of structural members inside buildings; 0.5 mil of Zn may be dissipated in 10 yr or less. Zinc plated steel in such locations is usually given a protective coating of paint.

Chromate conversion coatings are frequently applied to zinc plated parts for indoor use, to retard corrosion from

Table VI. Average Service of Unprotected Zinc Coatings on Steel in Outdoor Atmospheres

Coating Thickness, mils	Service, years			
	Rural	Temperate Marine	Industrial Marine	Highly Industrial
0.2	3	1	1	0.5
0.5	7	3	2	1
1.0	14	7	4	3
1.5	20	10	7	4
2.0	30	13	9	6

intermittent condensation such as may occur in unheated warehouses. Colored and clear chromate films minimize staining from fingerprints and provide a more permanent surface appearance than bare zinc.

Zinc plated steel is not commonly used for equipment that is continually immersed in aqueous solutions, and must not be used in contact with foods and beverages because of dangerous physiological effects.

Zinc may be used in contact with gases such as carbon dioxide and sulfur dioxide at normal temperatures if moisture is absent. For applications involving close-fitting moving parts, cadmium is preferred to zinc because the bulky white corrosion products of zinc may interfere with the motion of the parts.

Zinc gives satisfactory service on electroplated parts subjected to mild abrasion or erosion. It spreads under impact and, even though it is ruptured or driven into gouged or nicked areas, it continues to protect the exposed area by galvanic action.

Typical Applications. Electrodeposited zinc is used extensively to protect steel aircraft propeller blades, which are subjected to all extremes of outdoor exposure, as well as to damage from severe abrasion by sand and gravel on airport runways, and erosion by rain and hail. Also, this is an application in which the coating must not affect the fatigue properties of the steel adversely; zinc is one of the few coatings that meet this requirement. If the blades are to be painted or lacquered, the zinc coating is phosphated or chromated to provide a good base for paint.

Zinc is suitable for this application because it meets all requirements, particularly the sacrificial protective quality that helps to prevent corrosion even after severe abrasion. Conversion treatments of the chromate or phosphate type increase resistance to corrosion in addition to providing a good base for paint or enamel.

If zinc is applied to parts that have been heat treated to high hardness or that have been cold worked, the plated part should be held at 375 F for 1 to 3 hr to avoid hydrogen embrittlement.

Zinc without subsequent treatment forms a white corrosion product that detracts from the appearance of the part. Although the corrosion products do not necessarily indicate corrosion damage to the basis metal, they usually appear as a forerunner to complete penetration of the zinc and corrosion of the basis metal. The zinc plating is usually 0.1 to 1.5 mil thick.

A satisfactory coating for parts such as those on the inside of an office machine must afford protection in storage, assembly, and service (enclosed within a cabinet and not handled). The cost is important also. Gears, cams and other parts of the working mechanism can be plated with 0.15 to 0.25 mil Zn to meet these requirements. The cost for cadmium plating would be somewhat higher than for zinc.

Steel fasteners, such as screws, nuts, bolts and washers, are often electroplated for corrosion resistance and appearance. If protection against corrosion is the sole objective, zinc is the most economical coating metal. Coatings of 0.2 to 0.3 mil give protection for 20 yr or more for indoor applications in the absence of frequent condensation of moisture. Chromate coatings are used often to retard corrosion from condensates, to provide a more permanent surface appearance and to prevent finger marks. For indoor use in industrial areas and in locations where condensation is prevalent, as in unheated buildings, corrosion may be rapid, and the zinc surface should be phosphated and then painted so as to extend its service beyond the few years that would be obtained by the unpainted coating.

The dimensional tolerance of most threaded articles, such as nuts, bolts, screws and similar fasteners with complementary threads, normally does not permit the application of coating thickness much greater than 0.15 mil. The limitation of coating thickness on threaded fasteners imposed by dimensional tolerances (including class or fit) should be considered wherever practicable, to prevent the application of greater coating thicknesses than are generally permissible. If heavier coatings are required for satisfactory corrosion resistance, allowance must be made in the manufacture of the threaded fasteners for the tolerance necessary for plate build-up. If this is not practicable, phosphating before assembly and painting after assembly will increase service life. Approximate durability of 0.2 mil untreated coatings is given in Table VI.

A coating for steel fasteners harder than Rockwell C 34 requires a plating bath that will deposit a sacrificial metal of low coefficient of friction, for ease of assembly, and with minimum danger of hydrogen embrittlement. Cadmium has a considerably lower coefficient of friction than zinc, and cadmium plated from alkaline or acid baths, or lead plating, is generally the best selection. Alkaline zinc plating can be used, but the hazard of embrittlement of the steel is greater.

Steel hardware for communications equipment such as relays must withstand indoor environments (no moisture condensation) for more than 20 yr. This requirement is met with 0.2 mil of electroplated zinc, which is then chromated to increase corrosion resistance and permanence of surface appearance in storage and use. Other items finished in this manner for general use in communications equipment are steel brackets, lugs, fasteners and covers. (Finishes for relay armatures and cores are described in the section devoted to nickel-chromium coatings, page 103.)

A variation in the usual service condition can cause premature failure of a properly coated item. An example of this is the rusting of steel brackets in individually housed communications units each containing a silica gel desiccant to insure a dry environment at the operating temperature of 150 F. When incompletely dried desiccant was inadvertently used, moisture was driven off during operation of the unit and condensed on the cooler parts of the equipment. The steel brackets, protected with 0.2 mil Zn and a chromate coating, corroded within a year.

Copper-Nickel-Chromium

Composite coatings of copper-nickel-chromium, nickel-copper-nickel-chromium and nickel-chromium have been used extensively for protective and decorative purposes for many years. Since a decorative coating must remain attractive, it cannot provide sacrificial protection as cadmium and zinc do; therefore all metals anodic to the basis metal are precluded as coatings. The chief function of such coatings is to seal the basis metal hermetically with a combination of coatings, of which the final one is not attacked by the service environment. Absence of porosity in the underlying protective coating is of prime importance.

To remain decorative and bright, a coating must be smooth and reflective. Luster is also a necessary part of a decorative finish, so the electrodeposited coatings must be brightened either by mechanical or electrochemical means, or through the use of plating processes that include commercial brightening agents.

In this type of composite, the copper adjacent to the basis metal may vary from 0.1 mil to more than 50% of the composite thickness, and provides some protection. The copper may be buffed to obtain a smooth and bright deposit. The subsequent nickel coating can be deposited bright or may be buffed to obtain a smooth, bright finish. The nickel provides a corrosion-resistant barrier and a base for the chromium deposit. The final chromium coating is usually bright; its protective function is to impart resistance to tarnishing and abrasion. The coating is plated in a thickness of 0.01 mil.

Applications. In the selection of copper-nickel-chromium for applications such as business machines and cash registers, the factors considered are decorative value, protection from tarnishing during indoor service in offices and stores, and wear resistance.

External parts for accounting machines are plated with 0.1 mil Cu, 0.3 to 0.5 mil Ni, and 0.01 to 0.02 mil Cr. After exposure for 24 hr in the salt spray, or 1000 hr in the humidity cabinet (100 F, 100% relative humidity) this finish should show no corrosion. After exposure to salt spray for 48 hr, only 2 or 3 rust spots per sq ft will develop. This coating will withstand handling and wiping for 10 yr of indoor service.

Household and office fixtures that are frequently handled or used will give satisfactory service when plated to thicknesses mentioned earlier.

Automotive Bumpers. Nickel-chromium or copper-nickel-chromium combinations are the only plating metals satisfactory for protecting automotive bumpers against corrosion. The coating must withstand severe corrosion by salt on the highway, abrasion from sand, gravel and stones, and contact with other bumpers and objects. Since considerably more salt is being used on the highways during winter months, the problem of protecting bumpers from corrosion is increasingly difficult. Sudden loads such as caused by relatively minor impacts on the bumper will add stress to the electroplated deposits. Therefore the deposits must be ductile enough to withstand these stresses without cracking or flaking.

Electrodeposited composite coatings for automotive bumpers must be made on suitably prepared basis metal that is free from laps, seams, pits, rolled-in scale and other surface imperfections. The steel must be suitable for polishing without uncovering subsurface defects, but must not require excessive polishing to produce a surface satisfactory for plating. Corrosion resistance of the electroplate is greatly influenced by the surface of the basis metal.

The ASTM specifications for nickel-chromium coating thicknesses are summarized in Table V. The thicknesses generally used on automotive bumpers are given in Table III.

Cu-Ni-Cr Coatings for Zinc Die Castings

Porosity is one of the most important factors affecting the corrosion resistance of zinc plated with the composite (copper-nickel-chromium) coating. Deposits of at least 1 mil total thickness are required to eliminate porosity in the coatings.

Total plating thickness of 1.2 mils (including at least 0.6 mil Ni) is required to withstand one year of atmospheric exposure in Detroit with less than four blisters per sq in.; and a total plate thickness of 2 mils (including 1.5 mils Ni), to withstand one year of exposure with less than one blister per sq in.

Corrosion resistance of the coatings is closely related to the type and condition of the plating bath. The performance of the plated die casting is affected more by variables in processing the die castings and in the plating procedures than by the compositions of the various bright nickel baths used for plating of these parts. However, impurities in nickel plating baths adversely affect appearance, ductility and corrosion resistance. Since both appearance and ductility can be appraised readily, the presence of impurities can be detected before a coating of inferior corrosion resistance is applied to many parts.

The minimum satisfactory thickness of copper plate is 0.2 mil; corrosion resistance improves as nickel thickness increases to 0.8 mil, but above this the increase in corrosion resistance is not proportional to the increase in thickness of nickel. Figure 4 shows the change in rating on zinc-base die-cast panels plated with copper-nickel-chromium, after 1 yr exposure about 200 ft from the ocean at Miami, Fla. The slight difference in rating of the panels plated with 0.5 mil Cu plus 0.5 mil Ni-Cr and those plated with 0.3 mil Cu, 0.5 mil Ni-Cr is not significant, being within the limits of experimental error. The data in Fig. 5, from panels exposed at Pittsburgh, show that thicker nickel deposits give better corrosion protection and that a difference in 0.3 and 0.5-mil Cu undercoat for 0.5-mil Ni-Cr did not contribute to the corrosion resistance of the composite coating of Cu-Ni-Cr.

Figure 6 reports the data obtained on panels exposed in Detroit during the same period. The panels with nickel coatings of 0.8 mil or more withstood the February environment with only slight effect on the coating.

The ratings of various thicknesses of copper, nickel and chromium, after testing in Detroit, are given in Fig. 7. The results of exposure during the winter months show the superiority of total coatings of 1.25 mil, compared with those of 0.6 and 0.8 mil. Figure 8 gives a comparison of the corrosiveness of test environments at Cleveland, Miami, New York and Detroit, as shown by the performance of panels with 0.8-mil total coating. Results from the same test locations are compared for coatings of 0.6 and 1.5 mil in Fig. 9. The rating of the panels exposed at Miami was the same after one year for all the plate thicknesses tested and illustrates that an atmosphere containing salt alone does not cause the failure of these coatings on zinc die castings.

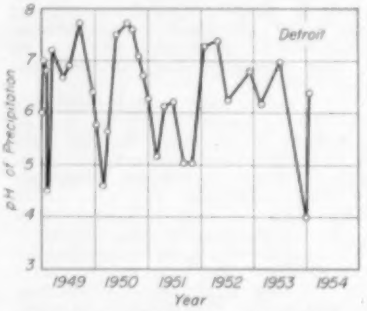

Fig. 10. Record of pH of Precipitation Collected from January 1949 to February 1954 in Detroit

The variations in pH of precipitation falling on the Detroit location used for exposure of the plated panels are shown in Fig. 10. Each point on the chart represents the pH of liquid collected for one to four weeks. The period for collection of each sample depended on the time necessary to obtain approximately one liter of solution in the collecting device. Strong acidity (about pH 4) of the rain and snow is not uncommon.

It was also found that, after the coatings had been perforated by the corrosive atmospheric constituents, the rate of deterioration was accelerated by de-icing salt solutions from highways. In Detroit, salt is used from November 1 to March 31. Road slush has been collected and analyzed on days when de-icing salt is spread, and salt content has been a little more than 5%, which is a strong corrosive on a

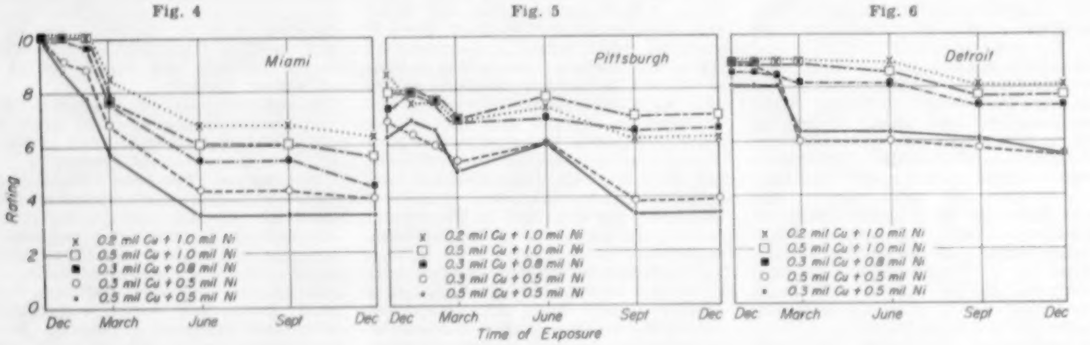

Fig. 4 to 9. Corrosion Ratings for Copper-Nickel-Chromium Deposits on Zinc-Base Die Castings in Exposure Tests at Miami, Pittsburgh, Detroit, Cleveland and New York City zinc die casting if the plated coating is perforated.

These data indicate that a 1.2-mil coating (total plate thickness) will give the minimum expected protection to zinc die castings for exteriors of automobiles operated in the Detroit area. Of this total plate thickness, at least half should be nickel.

Ni-Cu-Ni-Cr

Nickel is sometimes deposited on the basis metal for corrosion resistance and to permit the acid type of copper plating baths to be used. This coating is usually of the flash type, 0.1 mil thick or less. The copper provides some protection and is sometimes buffed to cover imperfections in the underlying metal and provide smoothness and brightness for the final coating. The second nickel coating also provides corrosion resistance and functions as a base for the subsequent chromium deposit. This nickel deposit may be buffed if necessary. The final deposit, chromium, furnishes resistance to tarnish and abrasion and is usually bright as deposited, although buffing is sometimes desirable. The chromium coating is usually 0.01 mil thick.

Nickel-Chromium

This composite requires less equipment and fewer operations than either copper-nickel-chromium or nickel-copper-nickel-chromium. The nickel provides resistance to corrosion and can be produced smooth and bright by mechanical means or as deposited. Deposited directly on the steel, nickel provides a base for the subsequent chromium deposit. In this composite, thickness of nickel is virtually equal to the specifications for the total plate.

The chromium deposit is usually bright and can be buffed if necessary. It provides resistance to tarnish and abrasion and is ordinarily 0.01 mil thick.

If it is determined that a bright coating, resistant to corrosion and abrasion, is required (that is, a nickel-chromium sequence of some sort) the selection of nickel-chromium in preference to copper-nickel-chromium or nickel-copper-nickel-chromium is determined by the condition of the basis metal, the degree of final lustre required and available facilities. On steel, it is often more economical to copper plate and buff before plating with nickel and chromium than to purchase a better grade of steel. Where the basis metal can be buffed easily, nickel is almost invariably plated directly on it.

The buffing of the copper will remove some defects in the basis metal and provide a good surface for the bright nickel, which in turn will assist in producing a chromium deposit of acceptable appearance. As an alternate procedure, an imperfectly prepared basis metal may be plated with nickel alone, or copper plus nickel, which can be buffed to an acceptable finish if it is soft enough. If, however, a hard, bright nickel is deposited, it must be plated on steel that is highly finished, or on buffed copper. Buffing is neither economical nor suitable on hard nickel deposits.

The relative resistance to corrosion of the two systems is about equal, provided that if a copper deposit is used it is deposited smoothly or, preferably, that it is buffed to smoothness. The nickel should be 0.6 mil min when copper is used.

A dull nickel deposit from the Watts-type bath has better resistance to corrosion than a semibright or a bright nickel deposited from an organic variation of the Watts bath. Cost considerations favor selection of the latter for a large number of applications.

Typical Applications. Nickel-chromium finishes in which the chromium is thicker than that required for decorative purposes, provide a combination of protection against corrosion, resistance to wear, and freedom from sticking. Finishes for telephone relay armatures and cores (silicon iron or steel) frequently consist of 0.2 mil Ni (Watts type) and 0.08 mil Cr. The wear on the bearing surfaces of such parts results from a combination of rapid intermittent impact and low-amplitude (< 1 mil) sliding motion. The latter produces an effect similar to that resulting from fretting wear or fretting corrosion.

Standard tests for wear do not give a reliable prediction of performance, but results from service have shown that 0.08 mil Cr will resist wear satisfactorily for many millions of operations. The bright chromium has a Vickers hardness from 800 to 1000. The nickel undercoat provides protection against corrosion for the magnetic iron structures for the life of the relay (often longer than 30 yr indoors), and a base for the chromium.

On certain special-purpose relays the chromium layer acts as a nonmagnetic barrier between core and armature. The "slow-release" type of relay uses 0.16 mil Cr (on 0.2 mil Ni) for this purpose. The nickel-chromium plating on moving relay parts has resulted in more reliable operation than coatings of zinc or cadmium or of nickel alone.

Selection of a coating for metal indoor furniture involves styling considerations as well as resistance to abrasion and to mild indoor corrosion. Experience with white brass and zinc during periods of nickel shortage demonstrated the general demand for a coating having a reflective surface that would remain bright. This is best provided by nickel-chromium or copper-nickel-chromium. The choice between the two is determined by the condition of the basis metal and the finishing facilities available. Normally the least complex plating schedule is most satisfactory—in this instance bright nickel and chromium. A large fabricator, making his own tubing and equipped to polish the weld, will need only to remove the orange peel at the bend before plating. A bright nickel coating 0.5 mil thick is followed by 0.02 or, more often, 0.01 mil Cr. If production is not large and the quality of the steel is poorly controlled, a copper plate followed by buffing will underlie the bright nickel and chromium. Normally, the least complex plating schedule (bright nickel and chromium) is most satisfactory.

The function of an over-the-counter item generally has little to do with the selection of a preferred coating schedule. Mild resistance to corrosion is usually needed and sometimes a hard deposit has an advantage. Price is not an important factor. Appearance or "sales appeal" is important.

For example, a suitable coating for a pair of pliers is selected on the basis of appearance, which should last until the item is sold and as long thereafter as possible. Bright zinc plating would appear to be the least costly that still provides the necessary protection against rust. Zinc coatings, however, darken with storage. Therefore, although pliers plated with a thin nickel-chromium deposit may rust earlier in service than those plated with zinc, the best guarantee for a snappy appearance in the showcase is nickel and chromium. "Quality" items of this kind are coated with 0.3 mil Ni and enough (0.002 mil) Cr to cover, which provides a deposit of great appeal and the assurance that the initial brightness will be maintained until the item leaves the store.

Second choice is nickel alone, but nickel electrodeposits will also dull somewhat and lack the attractiveness of chromium. Bright cadmium (0.1 to 0.2 mil) is cheaper than nickel-chromium. It should be used on hardened steel parts of complex shape because of less risk of hydrogen embrittlement and greater throwing power.

In selecting a coating for a novelty item, such as a steel key-chain, three requirements must be met: protection against rusting, resistance to wear and a bright decorative finish. A nickel-chromium coating meets such requirements readily.

The novelty item is not required to give long service and the corrosion is not severe. A coating of 0.25 mil Ni and 0.01 mil Cr should be satisfactory. The nickel can be deposited bright or dull, but the latter would require burnishing before chromium plating. Nickel is one of the coatings most resistant to wear, and the thin, decorative chromium coating withstands scratches and tarnish.

A bright zinc or bright cadmium coating of equal thickness will give excellent protection to the steel. However, an organic coating will be required to give permanence to the bright finish. Neither zinc nor cadmium resists wear as well as nickel does. Tin would neither resist wear nor protect the steel.

Decorative finishes on steel fasteners for indoor use consist of 0.2 mil Ni, sometimes with a flash of chromium for tarnish resistance. This coating, more expensive than a zinc coating of equivalent thickness, will give protection against corrosion for more than 20 yr in most indoor locations.

Substitutes for Cu-Ni-Cr

Copper-Chromium. Substitute coatings of 0.5 mil Cu and 0.01 mil Cr have been used in plating automotive steel parts for interior applications, but some nickel (0.1 to 0.3 mil) is required under the chromium to give good "color" and also to provide resistance to corrosion by perspiration. Horn rings, gear shift levers and other parts that are handled frequently have failed prematurely when finished with copper-chromium. The cost of copper-chromium plus clear enamel is usually greater than the cost of copper-nickel-chromium.

Tin-Nickel Alloy. The alloy bath for this coating is difficult to control, and the normal appearance of copper-nickel-chromium or nickel-chromium plating cannot be matched. The shortcomings of tin-nickel alloy include brittleness and the need for mechanical polishing to produce the desired brightness. Furthermore, this deposit has a faint rose-pink color which, in automotive applications, would have to be masked by an overplate of chromium in order to satisfy buyer preference.

When used, these alloy coatings are ordinarily 0.2 mil of tin-nickel alloy plated over 0.2 mil Cu.

"White Brass". The color of this alloy (about 80% Zn and 20% Cu), its brightness and ability to take an overplate of chromium are its principal advantages. However, it is brittle and, on outdoor exposure, forms considerable white corrosion product. An overlay of chromium causes formation of red rust (known as pore rusting) on the underlying steel. Preferred thickness is 0.2 to 0.3 mil of the Zn-Cu alloy.

Other Substitutes for copper-nickel-chromium on parts for interior use include 0.2 to 0.3 mil antimony, vacuum metallized aluminum (on plastic parts), buffed aluminum, anodized aluminum, and buffed type 430 stainless steel. None is satisfactory except buffed stainless steel. On the basis of their desirability as substitutes, buffed type 430 stainless steel rates first, then anodized aluminum, buffed aluminum, tin-nickel alloy, white brass, antimony and vacuum metallized aluminum. However, with anodized aluminum, dyed anodized aluminum, or other colored finishes, the problem of matching color is a real one. To add to this problem, many colors used in production of these coatings are unstable.

Nickel

Nickel plate, with or without an underlying copper strike, is one of the oldest protective-decorative and decorative electrodeposited metallic coatings for steel, brass and other basis metals. The first applications of nickel plate were for protection and beautification of stove and bicycle components. Coating thickness varied widely, depending on function and service requirements.

Nickel plate tends to yellow on long mild exposure, and will turn green on severe exposure if not polished occasionally. The introduction of chromium plate in the late 1920's overcame the tarnishing problem, and led to a great increase in the use of nickel, as a component of protective-decorative coatings, in various combinations with copper and chromium.

The principal present uses for nickel plate without a subsequent chromium deposit are based principally on cost. This applies to decorative coatings.

Heavy dull nickel deposits (3 to 10 mils) are being used increasingly for industrial and engineering purposes.

If a "wrought iron" finish is desired on household furniture such as a floor lamp, nickel will protect the basis metal, and its color in a dull brushed finish is similar to clean iron. The dark oxidized appearance of portions of a wrought iron object can be simulated by depositing a thin "black nickel" coating over the nickel. The highlights are then relieved by brushing with pumice to expose the ironlike nickel undercoat. A final clear organic coating gives permanence to the finish and affords additional protection.

The thickness of the nickel may be 0.2 to 0.3 mil, and the black nickel coating should be only thick enough to give the desired dark color. Black nickel cannot be plated thicker than 0.1 mil; a cheaper way to get a black finish is to give the metal a blackening treatment with heat.

Nickel can be electrodeposited so that the range of stress in the coating is from 40,000 psi in tension to 10,000 psi in compression. For resistance to fatigue, a nickel plate of 5,000 to 10,000 psi in compression is preferable to one in tension.

Copper

Copper plate is used for protection against corrosion in very mild atmospheres, although its tendency to tarnish makes it less desirable than other types of plating where prevention of corrosion is the main factor. Electroplates of copper as thick as 0.5 mil are used for parts exposed only to indoor storage.

A copper flash plate is used occasionally to identify similar parts that might be mixed if unplated. If two parts of the same size are made of different steels or are heat treated differently, one piece might be copper plated for identification only.

Typical Applications. Copper plating is used extensively for decorative purposes. On lamp bases or other furniture, the finishing schedule is to plate one mil Cu, buff to a high luster, and then apply a clear lacquer to prevent tarnishing of the copper. This sequence has the disadvantage of requiring a repolish and relacquer if the lacquer wears off or is removed.

A decorative copper coating is used on some hardware for caskets and furniture that is to simulate bronze. The parts are plated with 0.5 mil Cu, treated with sulfide to blacken the surface, and then brushed to create a rich antique bronze effect. To retain this finish for a storage life of at least 5 yr, the plated and brushed surface must be lacquered.

Brass

Electrodeposited brass is sometimes selected as a coating for hardware and ornaments because of its color.

Typical Applications. Ordinarily a brass coating on an item such as a steel or cast iron doorknob will be no thicker than 0.1 to 0.15 mil. The color of the plating must match other yellow brass hardware components. Its wear resistance, permanence of finish and protective value depend on the quality of a clear organic coating applied after buffing the brass deposit. For this reason there is little to be gained by increasing the thickness of the brass, and to do so would increase its cost needlessly.

Other items that might be plated similarly include luggage hardware, belt and suspender buckles, cabinet hardware, lamp stands and bases, and novelties. The brass plating on these items is primarily for color or appearance and is applied to ferrous metal articles as a substitute for more expensive cast or wrought brass.

Brass plated hardware is not usually specified for outdoor service. There are no standard specifications for brass plating on ferrous metals.

SPECIAL-PURPOSE ELECTROPLATES

The deposits for special applications include brass for rubber adherence, silver-lead-indium deposits for bearings, silver for electrical conductivity, zinc-tin and lead-tin alloys for soldering, copper and copper-tin alloys for stop-off during carburizing and nitriding, hard chromium for abrasion resistance, and silver, lead or tin for resistance to galling. The requirements of these applications differ greatly.

Bonding of Rubber

The determining factor in the selection of brass plating for rubber adherence is the fact that of the metals (brass, copper, cobalt, Monel and steel) to which rubber can be bonded with cements, brass gives the strongest bond. The strength of this bond depends on the composition of the brass in relation to that of the rubber. This special strength is attributed to a chemical bond created by a sulfide interlayer between the two surfaces. The composition of electrodeposited brass can be varied readily as required.

The strength of the bond is usually determined by a tear test (peeling the rubber from the metal surface) or a vertical pull of the rubber in tension. Failure should occur in the rubber, not in the relatively thin (0.02 to 0.05 mil) brass coating. For special applications where maximum bond strength is needed, 0.2 to 0.5-mil plate is used.

The brass alloy composition for a given rubber stock must be held within close limits for satisfactory adhesion. A copper content of 70 or 75% is usual, although by proper compounding of the rubber stock, alloys containing from 60 to 80% Cu have been used successfully. Arsenic, lead and nickel in the brass decrease the strength of the bond. Baths must be free from both metallic and organic impurities.

Electrical Connections

Cadmium coating of 0.2 mil is used occasionally as a solderable finish. Actually it is less solderable than some of the composite coatings (for example, copper-tin) but is sometimes preferred because it is applied in a single operation; composite coatings require two.

Cadmium-Tin. For steel parts of electrical control devices that will be exposed to severe corrosive conditions around pickling tanks in steel mills, a satisfactory electrodeposited coating consists of 0.25 mil Cd plus 0.25 mil Sn. This composite coating is suitable for parts that are subject to sliding friction or that are to be soldered after assembly. For highly corrosive service conditions, parts that require soldering must be lacquered after assembly. If the parts are stationary and do not require soldering after assembly, clear lacquer can be applied before assembly.

Copper plating provides surfaces that will braze or solder readily. Some radio and television chassis are copper-plated (0.1 to 0.3 mil) and then coated with an organic finish to protect the copper from tarnish.

Copper-Tin. A coating of 0.2 mil Sn on brass terminals and lugs is preferred for rapid soldering of connections. A copper undercoat of 0.2 mil is needed to prevent loss of solderability, which otherwise occurs in a few weeks to the extent that quality connections cannot be made with rosin flux.

Lead-Tin electroplated coatings also provide solderable surfaces on brass, but they do not have the solderability of copper-tin when a nonactive (rosin-alcohol) flux is used. The coatings vary in thickness from 0.1 to 1 mil, depending on requirements.

Electrodeposits of lead-tin alloys plated directly on steel are commonly used as an aid in soldering electronic equipment, and specifically as a preferred alternate for coatings of tin without copper or nickel undercoats. Alloys containing 20 to 25% Sn have been used successfully, but a composition with 40% Sn has the best oxidation resistance, flow and soldering characteristics, and heat of fusion.

Silver plate is used extensively for stationary and moving electrical contacts because of its excellent electrical conductivity. It has a lower contact resistance than most metals, an unstable oxide, and a sulfide that has low contact resistance and is easily broken through by the current. Table VII compares the contact resistance of bare copper with that of copper plated with silver and tin.

Table VII. Contact Resistance of Copper Electroplated with Silver and Tin

Plate	Contact Resistance, microhm: Initial Clean Square Bars[a]	After Passing 500 amp for 300 hr	Joints Separated and Aged 300 hr at 185 F	After Passing 500 amp for Additional 2000 hr	Ratio of Final to Initial Resistance
Silver[b]	0.38	0.48	0.89	0.22	0.58
Tin[b]	2.74	3.00	3.90	3.46	1.46
Bare Copper[c]	6.34	5.44	367	877	138

(a) Bars ¼ by 2 by 4 in. (b) 0.5 mil thick. (c) Plated with 0.5 mil Cu

Tin. Electrodeposited tin is used in thicknesses of 0.2 to 0.5 mil to facilitate soldering of electronic and electrical components. Because of its good lubrication qualities and low electrical contact resistance, tin is used frequently for coating electronic tube bases and other plug-in components. Plate thicknesses vary from 0.1 to 1 mil, depending on the protection required against corrosion and wear. Brightening of tin by flowing with heat is done best with a thickness of 0.25 mil max that has been plated on nickel or copper strike coatings. During storage, however, tin acquires an oxide film that prevents ready soldering unless corrosive fluxes are employed.

Hard Chromium

Because of its hardness, low coefficient of friction and excellent release characteristics, hard chromium plate is generally used for plating molds in thicknesses of 0.1 to 3 mils, depending on the tolerance requirements and the abrasiveness of the molding stock. To facilitate mold release, the molding surfaces should be given a high polish (<2 micro-in. finish) before and after chromium plating. Unless corrosion-resistant tool steels are used (high nickel), a 0.5-mil min plating of hard chromium is preferred for reasonable resistance to corrosion.

Typical Applications. For the high pressures encountered in molding phenolic parts of complex shape, a mold of hardened tool steel (Rockwell C 59 to 61) is a prerequisite to chromium plating for satisfactory mold life. For the handling of abrasive molding compositions containing fiber glass, a plating of at least 2 mils and preferably 5 mils is required to give a reasonable mold life before stripping and replating are required. There is no substitute finish for hard chromium plate.

The increase obtained in the durability of the cutting edges of tools by plating them with chromium is illustrated by the following examples: (1) a spiral drill (high speed tool steel), used on ¾ hard brass with 100-sec paraffin oil, served for 524 operations before chromium plating and for 2933 operations after chromium plating; (2) a chromium coating between 0.05 and 0.1 mil thick on a high speed form-cutter for a circle mill increased tool life 500%.

To prevent hydrogen embrittlement, tools should be given a stress relief treatment before hard chromium plating and should be baked after plating. Specific time and temperature vary with the alloy and application.

Coatings for Bearing Surfaces

A satisfactory coating for bearings must resist fatigue, corrosion, scoring and embeddability, usually in that order of importance. For service involving high speeds and high unit loads, the silver bearing (silver-lead-indium) will last thirty times as long as a babbitt bearing, and ten times as long as a copper-lead bearing. It costs approximately twice as much as a copper-lead bearing, but this is justified by the increased life. Thickness varies from 20 to 60 mils.

The adherence of the silver to the steel backing should be stronger than 25,000 psi, which is the tensile strength of the annealed electrodeposited silver. Silver plated directly on steel has a bond strength of about 20,000 psi, as determined in a miniature adaptation of the Ollard test. The bond strength after annealing is more than 35,000 psi for silver on a nickel strike. A copper strike gives lower bond strength than a nickel undercoat.

Typical Applications. A thickness of 0.5 to 1.5 mil of electroplated silver on steel prevents seizure and galling of surfaces in contact with other steel, bronze, beryllium-copper or aluminum alloy parts under heavy load conditions. The silver is easily plated from a cyanide bath, if care is taken to strike properly the metal to be plated, so as to insure the desired adherence. Hardness of the silver can be controlled through the use of high or low current densities during plating. The softer deposits obtained by using low current densities are generally preferred for these applications.

Silver plating has been used advantageously on large roller and ball bearings on the outside diameter of the outer race, the inside diameter of the inner race, and on threaded parts that support thrust loads. Silver plating is better than copper in minimizing stress concentration caused by surface irregularities in mated parts that operate under high stresses.

Copper plating in thicknesses of 0.1 to 0.3 mil is used sometimes as an anti-galling agent for initial break-in on highly loaded gears. However, the manganese phosphate treatment is now more commonly used, because it is cheaper and produces surfaces that have better oil retention, which is desirable for break-in of gears.

Rebuilding Worn and Undersize Parts

The principal use of iron plating is for replacing metal on parts that have been worn or machined undersize. For this purpose its advantage over nickel and chromium plating is that the deposit is softer, more ductile, easier to machine and can be hardened by carburizing. The plating process for iron is more difficult to control than plating processes for nickel and chromium. Depending on bath composition and operating conditions, iron can be deposited with hardness ranging from Brinell 127 to 350 and tensile strength from 47,500 to 110,000 psi.

Stop-Off Coating

Electroplated copper is used as a stop-off in carburizing and nitriding operations and as a protection for steel parts during heat treatment. Bronze plating is also used for stop-off in nitriding.

Typical Applications. One of the most common uses of copper plate by itself is in stopping off or protecting selected areas during carburizing and nitriding. A dense copper plating 0.3 mil thick will protect steel at carburizing temperature up to 1750 F for 5 hr, but it is safer to use 0.5 mil Cu. Steel can be protected for at least 8 hr at carburizing temperature with 0.5 mil min of copper plate. However, if the finish of the parts is not smooth and free from machining slivers or fragmented edges, no practicable thickness of copper will give adequate protection.

In specifying a coating thickness, it must be remembered that some areas may receive low current density during plating; therefore the thickness should be specified for these areas so that adequate protection will be provided. During carburizing or nitriding, precautions must be taken to prevent exposure of the parts to oxidizing atmospheres at elevated temperature.

A dense plate 0.5 mil thick will give protection for 72 hr against nitriding atmospheres operating to 1050 F, although 0.7 mil is preferable for cycles approaching this limit. Copper plate has proved more desirable than tin, which becomes alloyed with the steel, because copper is more readily stripped after nitriding. Bronze plating is sometimes used.

For the protection of parts during hardening, copper brazing, and rehardening operations, a copper plate of 0.1 to 0.3 mil protects against decarburization or further carburization.

Copper plating is sometimes used to protect parts from an oxidizing atmosphere in tempering furnaces, at temperatures not over 1200 F. A thickness of 1 mil will protect steel for 1 hr in an oxidizing atmosphere at 1200 F; most of the copper will be oxidized in that period.

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Induction Hardening and Tempering

By the ASM Committee on Induction Hardening

THIS ARTICLE deals with the selection and control of equipment and metal for commercial hardening and tempering by induction heating. Results of some typical production applications are presented.

Commercial Equipment

Induction hardening is generally done at frequencies of 1000 cycles per sec or higher. The types of high-frequency equipment commercially available and pertinent data concerning each type are shown in Table I.

Motor-generator units consist of a high-frequency generator driven by a motor. Induction motors, which may be mounted integrally with the generator or separately on a common base, are used with 10,000-cycle* generators. The integrally mounted units can be either vertical or horizontal.

The motors for generators of 1000 to 3000-cycle frequencies may be of either the induction or synchronous type. Units using a synchronous motor are mounted horizontally and separately from the generator. The data in Table I cover ratings when units are used with a 60-cycle power supply. Many motor-generator units may be used with 50-cycle sources with proportionate decreases in generator frequency and slight changes in ratings.

Spark-gap units consist of an electrical circuit that alternately charges and discharges a capacitor by means of a spark-gap arrangement. The 25, 50 or 60-cycle supply voltage is increased to several thousand volts by an input transformer. The secondary or high-voltage terminals of the transformer are connected to a capacitor through choke coils constructed to allow passage of low-frequency current but to restrict the flow of high-frequency current set up by the discharge of the capacitor. The spark-gap arrangement acts as a valve that permits the capacitor to discharge periodically. The work coil or inductor is connected in series with the spark gaps to complete a circuit for the discharge of the capacitor. The frequency, fixed by the inductance and capacitance values in the discharge circuit, is in the range of 20,000 to 600,000 cycles.

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Induction Tempering

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Electronic tube units consist of a power supply section and an oscillator section. The power section provides the high voltage for the oscillator tube after rectification to a pulsating direct current, usually by mercury-vapor tubes. The oscillator tube and a tank circuit consisting of a matched inductor coil and capacitor comprise the oscillator section. The oscillator tube controls the amount of electrical energy delivered to the tank circuit from which it is removed by the coupled load. A small and proportionate amount of the power in the tank circuit is fed back into the grid of the oscillator tube to control the current that is delivered to the tube, and it in turn controls the amount of electrical energy entering the tank circuit. The frequency developed in the converter is determined by the inductance of the tank coil and the capacitor, which form a parallel tuned circuit. A load-matching network electrically coupled to the tank circuit is used to transmit tank circuit energy to the work.

Supersedes the information on induction hardening and tempering on pages 280 to 282 of the 1948 ASM Metals Handbook

Power and Frequency

Any electrical conductor can be heated by electromagnetic induction. As alternating current from the converter flows through the inductor or work coil, a highly concentrated, rapidly alternating magnetic field is established within the coil. The strength of this field depends primarily on the magnitude of the current flowing in the coil. The magnetic field thus established induces an electric potential in the part to be heated, and since the part represents a closed circuit, the induced voltage causes the flow of current. The resistance of the part to the flow of the induced current causes heating by I^2R losses. This is similar to what occurs in a simple transformer; the work coil represents the primary, and the part the secondary.

The heating depends on the magnetic and electrical characteristics of the work, and on the frequency of the alternating current as well as the magnitude of the current flowing in the work coil. For practical purposes most ferrous metals considered in induction hardening and tempering applications have values of electrical resistivity and magnetic permeability so similar that little consideration need be given these factors in the choice of equipment of proper power and frequency for induction heating.

The distribution of induced current in a part is maximum on the surface and rapidly decreases within the part; the effective penetration of current increases with a decrease in the frequency. The distribution of induced current is influenced also by the magnetic and electrical characteristics of the part heated; and since these properties change with temperature, the current distribution will change as the work is heated.

Because the heating proceeds to the

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*"Cycles per second" has been shortened to "cycles" throughout the text of this article.

Table I. Types and Characteristics of Induction Heating Equipment of the Three Principal Types

Motor-Generator Equipment

Generator Ratings (a)			Motor Ratings (60-cycle, 3-phase)				
Kw	Frequency, cycles per sec	Voltage	Hp	Type	Voltage	Construction	Cooling (b)
7.5	10,000	220	15	Induction	220/440	Vert/Horiz	F/W
15	10,000	220	25	Induction	220/440	Vert/Horiz	F/W
30	4,200	400	50	Induction	220/440	Horizontal	A
30	10,000	220/440	50	Induction	220/440	Horizontal	F/W
		200/400/800	50	Induction	220/440	Horizontal	F/W
50	3,000	200/400/800	90/75	Induction	220/440	Horizontal	A/F/W
50	10,000	220/440	90/75	Induction	220/440	Vert/Horiz	A/F/W
		200/400/800	90/75	Induction	220/440	Vert/Horiz	A/F/W
75	10,000	220/440	125	Induction	220/440	Horizontal	W
		200/400/800	125	Induction	220/440	Horizontal	W
100	3,000	400/800	150/175	Induction	220 up	Vert/Horiz	A/W
100	10,000	440	150/175	Induction	220 up	Vert/Horiz	W
		200/400/800	150/175	Induction	220 up	Vert/Horiz	W
150	3,000	400/800	250	Ind/Syn	440 up	Horizontal	W
150	10,000	440/880	250	Induction	440 up	Horizontal	W
		400/800	250	Induction	440 up	Horizontal	W
175	1,000	400/800	300	Induction	440 up	Vert/Horiz	A/W
175	10,000	400/800	300	Induction	440 up	Vertical	W
200	3,000	400/800	300	Ind/Syn	440 up	Vert/Horiz	A/W
250	1,000	400/800	350	Ind/Syn	440 up	Horizontal	A/W
250	10,000	440/800/880	350	Induction	440 up	Vert/Horiz	W
300	1,000	800	450	Induction	440 up	Horizontal	W
300	3,000	800	450	Ind/Syn	440 up	Vert/Horiz	A/W
350	1,000	800	500	Ind/Syn	440 up	Vert/Horiz	W
350	10,000	800	500	Induction	440 up	Horizontal	H
500	3,000	800	800	Ind/Syn	440 up	Horizontal	A/W/H
700	1,000	800	1000	Ind/Syn	440 up	Horizontal	A/W
700	3,000	800	1000	Ind/Syn	440 up	Horizontal	A/W
700	10,000	800	1000	Induction	440 up	Horizontal	A/W/H
1000	1,000	800	1500	Ind/Syn	440 up	Horizontal	A/W
1000	3,000	800	1500	Ind/Syn	440 up	Horizontal	A/W
1250	1,000	800	1950	Ind/Syn	440 up	Horizontal	A/W
1250	3,000	800	1950	Induction	440 up	Horizontal	H
1500	3,000	800	2100	Induction	440 up	Horizontal	H
2500	3,000	800	3750	Synchronous	440 up	Horizontal	H

(a) Generator may be given higher ratings for intermittent service. Multiple ratings indicate a choice of voltage is available at each kilowatt rating. For example, for item 4 in the table, one facility indicates 30-kw generator available with voltage ratings of 220 and 440; another facility indicates 30-kw generator available with voltage ratings of 200, 400 or 800, each with the same frequency. (b) A = open, air cooled; F = enclosed, fan cooled; H = hydrogen, water cooled; W = enclosed, water cooled.

Vacuum Tube Equipment

Output		Input			
Kw	Frequency, kc per sec	Phase	Voltage	Amperage	Cooling
1	800	1	115	17	Air
1	1600	1	115	17	Air
1	2500/3000	1	115/220	17/10	Air
2	3000	1	220	20	Air
2.5	400/700	1	220/440/550	27	Water
3	450	1	220	40	...
4	450	3	220/440	...	...
5	450/530	1/3	220/440	70/40	...
5	250/600	1/3	220/440/550	55/32	Water
5	2100	3	220	29	Air
7.5	250/600	1/3	220/440/550	65/38	Water
10	250/600	1/3	220/440/550	52/30	Water
10	450/530	3	220/440	70/40	...
12.5	2100	3	220	73	Air
20	180/600	3	220/440/550	105	Water
25	450/530	3	220/440	150/80	...
25	180/400	3	220/440/550	130	Water
25	2100	3	440	74	Water
30	180/400	3	220/440/550	175	Water
50	180/400	3	440/550	138	Water
50	450/530	3	220/440	300/150	Water
75	180/400	3	440/550	210	Water
100	180/400	3	440/550	275	Water
100	450	3	...	...	Water
200	450	3	440	...	Water
600	200	3	2300	...	Water

Spark-Gap Equipment

Output		Input				
Kw	Frequency, kc per sec	Phase	Voltage	Amperage	Cooling	Kw
0.25	200	1	115	5	Air	0.5
1	300/600	1	115/220	9 at 220 v	Air	2
2	300/600	1	220/440/550	18 at 220 v	Water	4
4	150/600	1	220/440/550	35 at 220 v	Water	7.5
4.5	40	1	220/440	60/30	...	6
7.5	150/600	1	220/440/550	70 at 220 v	Water	15
15	150/600	1	220/440/550	140 at 220 v	Water	30
15	30	1	220/440	125/65	...	20
30	20	1	220/440	250/125	...	40

interior by conduction as soon as the surface is heated, the actual depth of heating is determined by the heating time and the power density (kw per sq in. of surface within the inductor) as well as by the frequency. Maximum power density, minimum time of heating and high frequencies will produce a minimum case depth. The influence of these factors is apparent in Table II.

Selection of Frequency

In analyzing the frequency and power required for a specific application, it is desirable to consider the frequency first. Primary considerations are the depth of heating and the size of the part.

Table III lists the power sources and frequencies most commonly used in induction hardening. As shown in this tabulation, the lower frequencies are more suitable as the size of the part and the case depth increase. However, because power density (kw per sq in. of surface within the work coil or inductor) also has an important influence on the depth to which the part is heated, wide deviations from this chart may be made with successful results, since higher densities of power compensate for lower frequencies. This is particularly important where equipment of a given frequency already exists in the plant or where equipment is required for several different applications. In some instances, the determining factor in selecting the frequency is the power required to provide power density sufficient for successful hardening, since lower-frequency equipment is available with higher power ratings.

The use of wrong frequency will result in a decrease in electrical efficiency; sometimes in failure to maintain a minimum case depth where shallow cases are required; or in failure to heat uniformly throughout the piece where through hardening is required. Figure 1 illustrates the decrease in transfer of energy or heating efficiency that results when the wrong frequency is selected. While the efficiency for all frequencies is similar with large bar sizes, maximum efficiency is achieved with small bars by using higher frequencies. In parts of small diameter suitable hardening temperatures cannot be obtained with the frequencies shown in Fig. 1. Megacycle (million-cycle) frequencies are desirable for such parts, or the thin sections may sometimes be hardened successfully with normal frequencies by using a combination of induction heating and radiation from an induction heated liner that surrounds the part except for a slit along its length to prevent electromagnetic shielding.

Selection of Power

The size of the converter or the power required should be determined on the basis of the following factors:

1. Requirements for power density and the minimum time needed to produce the specified hardness, depth of hardness and length of section to be hardened. This information may be available from previous experience, from experiment or from data such as those in Table II.
2. The size of the section to be heated will determine the possible limits of power density available with a converter of a given size.

Table II. Experimental Data for Induction Surface Hardening of 1045 Steel
(Influence of Power Density,[a] Prior Structure and Frequency on Depth of Hardness)

Prior Treatment	Affected Depth, in.[b] 3000 c	Affected Depth, in.[b] 10,000 c	Affected Depth, in.[b] 500 kc	Hardened Depth, in.[c] 3000 c	Hardened Depth, in.[c] 10,000 c	Hardened Depth, in.[c] 500 kc	Heating Time, sec[d] 3000 c	Heating Time, sec[d] 10,000 c	Heating Time, sec[d] 500 kc
5 Kw per Sq In., Maximum Inductor Input[a]									
Annealed	0.178	0.152	0.126	0.143	0.125	0.096	6.4	7.6	10.5
Normalized	0.144	0.137	0.110	0.108	0.096	0.088	6.3	7.5	10.5
Quenched and tempered	0.116	0.103	0.048	0.096	0.070	0.042	7.0	7.3	7.8
10 Kw per Sq In., Maximum Inductor Input[a]									
Annealed	0.157	0.125	0.063	0.114	0.104	0.057	3.3	2.6	3.5
Normalized	0.122	0.105	0.062	0.093	0.089	0.057	3.2	2.6	4.0
Quenched and tempered	0.096	0.074	0.029	0.080	0.066	0.026	3.3	2.4	2.5
15 Kw per Sq In., Maximum Inductor Input[a]									
Annealed	0.148	0.109	....	0.110	0.094	....	2.4	1.4	...
Normalized	0.114	0.086	....	0.089	0.080	....	2.5	1.3	...
Quenched and tempered	0.088	0.067	....	0.072	0.062	....	1.9	1.2	...

(a) Power density per unit of hardened surface area. Power densities of 30 to 35 kw per sq in. may be used in scanning applications. (b) Minimum depth below surface where no appreciable change occurred in prior structure. (c) Depth below surface where hardness decreased to Rockwell C 50. (d) Minimum heating time that provided satisfactory structure

These data, for bars of 1^{3}_{8} in. diam, can be used for diameters above the knee of the curves (75% value) in Fig. 1.

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3 The shape and design of the part. If the part is suitable for "scanning" or progressive hardening (that is, hardening by traversing the part under or through an inductor and quench assembly that hardens only a small segment or band at one time) greater power densities may be obtained from the equipment. Progressive hardening is the only practicable procedure for the surfaces of long shafts, spindles and lead screws.

4 The production requirements should be stated in terms of a practical basis of working time, preferably pieces per hour, and should include an allowance for repairs and maintenance, operating efficiency (frequently taken as 80%), and future requirements, if known.

An estimate of the size of unit or power required may be made from the information relating to the above factors. From the power density and the minimum heating time required to meet specifications, the input of energy per unit of surface area within the inductor (kw-sec per sq in.) may be calculated. From the size of the part, the surface area may be determined, and from this the input of energy required to heat each piece successfully (kw-sec per piece). If the information available at this point indicates that the specifications for case depth and hardness pattern can be obtained only with a precise (critical) heating time, and scanning is not possible, the power required can be determined readily by dividing the energy input per piece by the critical heating time. If the specifications for case depth and hardness contour allow some latitude, the heating time may be increased with a corresponding decrease in power to keep the input of energy per piece essentially constant.

If the production rate based on the size of converter thus determined does not meet production requirements, then either two or more units of like capacity may be used, or a single unit having two, three or four times the capacity determined may be used to induction harden two, three or four pieces simultaneously in a multiple coil.

When the shape and design of a part are suitable, high power densities may often be obtained with relatively low-power units by scanning. Although such parts as cams, camshafts and crankshafts, because of their shapes, are not amenable to scanning, straight shafts, lead screws and spindles are. For such parts, the size of the unit is determined by reducing the production requirements to a rate of hardening (r) in inches per second, calculating the length of inductor (l) in inches from the minimum heating time (t) required ($l = rt$), then calculating the surface area of the part within the inductor (square inches), and finally calculating the total power input in kilowatts from the power density in kilowatts per square inch.

Example of Selection

Consider that it is required to harden the full length of the following shafts in a given plant:

1-in. diam by 6 in. long at 200 per hr
2-in. diam by 10 in. long at 160 per hr

The steel selected is 1045 in the normalized condition, and minimum hardness of Rockwell C 50 is required at a depth of 0.090 in. From Table III, the frequency and corresponding type of power source may be selected. For section sizes from 1 to 2 in. and case depths of 0.050 to 0.100 in. it may be noted that rating A has been given motor-generator equipment with a frequency of 10,000 cycles.

Power selection may be determined from data in Table II that give the power density and the minimum heating time needed to produce the required hardness and depth for various heat treated conditions of steel. For

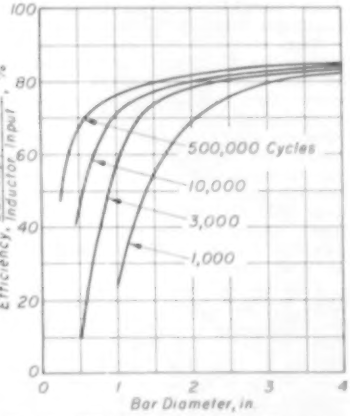

Fig. 1. Efficiency of Energy Transfer at Several Frequencies to 1045 Steel Bars of Various Sizes Heated to 2000 F. Inductor ID was 1.125 in. larger than bar OD. Megacycle frequencies are needed for hardening bars of the smallest sizes.

Table III. Selection of Power Source and Frequency for Various Applications of Induction Hardening[a]

Hardened Depth, in.[b]	Section Size, in.	Frequency: Power Lines, 50 or 60 c	Motor Generators 1000 c	Motor Generators 3000 c	Motor Generators 10,000 c	Spark Gap 20 to 600 kc	Vacuum Tube[c] over 200 kc
0.015 to 0.050	1/4 to 1					A	A
0.050 to 0.100	7/16 to 5/8				B	A	A
	5/8 to 1				A	A	A
	1 to 2			B	A	B	B
	Over 2		B	A	A		C
0.100 to 0.200	3/4 to 2			A	A	C	B
	2 to 4		A	A	B		
	Over 4		A	B	C		
Through Hardening	1/8 to 1/4					A	A
	1/4 to 1/2				B	A	A
	1/2 to 1			B	A	B	B
	1 to 2			A	A		
	2 to 4		A	A	B		
	4 to 8	B	A	B			
	Over 8	A	A				

(a) Indicated selections are rated A as most suitable, B as suitable, C as satisfactory. Considerable overlap exists and specific frequencies can be used successfully over a wide range of applications. (b) Depth below surface for minimum hardness of Rockwell C 50, as quenched. (c) Megacycle frequencies necessary for case depth less than about 0.015 in.

example, the values in Table II for the normalized structure indicate that a power density of 10 kw per sq in. at 10,000 cycles will produce a hardened depth of 0.069 in. in a minimum heating time of 2.6 sec, or it may be determined that an energy input of about 26 kw-sec per sq in. of surface is required. If an attempt were made to heat the entire 6-in. length at once, this would mean heating 6 in. × 1 in. × 3.142 (length × diam × π) or 18.8 sq in. of surface, and the power requirement would be 188 kw, considering a power density of 10 kw per sq in. as necessary.

Since these parts lend themselves to heating and quenching progressively (scanning), a second estimate of power may be made, using the same figures for power density, depth of case and heating time. To satisfy the production requirements for heating the part when it is passed through the inductor or heating coil progressively, the rate of hardening (r) should be:

$$r = \frac{\text{200 pieces per hr} \times \text{6 in. long}}{\text{3600 sec per hr} \times \text{0.8 operating efficiency}}$$
$$= \text{0.42 in. per sec}$$

To meet the minimum heating time (t) of 2.6 sec for successful hardening, the length of the inductor (l) must then be 0.42 in. per sec × 2.6 sec = 1.08 in. A power density of 10 kw per sq in. applied to a coil 1.08 in. long to heat a part of 1-in. diam would require a power input of

$$3.142 \times 1 \times 1.08 \times 10 = 34 \text{ kw}$$

A similar analysis for the 2-in. shafts yields:

$$\frac{\text{160 pieces per hr} \times \text{10 in. long}}{\text{3600 sec per hr} \times \text{0.8 operating efficiency}}$$
$$= \text{0.56 in. per sec,}$$

which is the scanning speed required to produce 160 pieces per hr. The length of the coil required is

$$\text{0.56 in. per sec} \times \text{2.6 sec} = \text{1.45 in.}$$
$$\text{and } 3.142 \times \text{2-in. diam} \times \text{1.45 in. long} \times 10$$
$$\text{kw per sq in.} = \text{91.3 kw}$$

The total power requirement is:

34 kw (for 1-in. diam shafts)
91.3 (for 2-in. diam shafts)
125.3

Referring to Table I, the total power requirement would be met with the selection of a 150-kw, 10-kc motor-generator unit.

In the example given, a choice is available in selecting either one generator capable of furnishing the total amount of power required, or two individual generators each capable of handling one hardening assignment — that is, a 50-kw and a 100-kw generator. The single large generator would be the better choice and would require a lower initial investment if the hardening operations were centralized or grouped. For widely separated locations, the cost of extra handling should be studied. This factor may place the multiple-generator arrangement on a more favorable cost basis; also the additional flexibility and insurance against total shutdown in the event of a single failure would favor the installation of two generators.

When data of the kind reported in Table II are not available, approximate power requirements may be estimated from the known values of the energy input required per unit surface area to produce given results. For example, the value of 35 kw-sec per sq in. is commonly used to represent the energy input required per sq in. for hardening plain carbon steel to a depth of 0.125 in. From this value the total input of energy required per piece may be determined by calculation, and then the power or size of converter may be estimated by using the time available to heat each part as defined by the production requirements. Obviously this technique does not assure that an acceptable hardness and hardness pattern will be obtained, so it should be used only as a preliminary estimate.

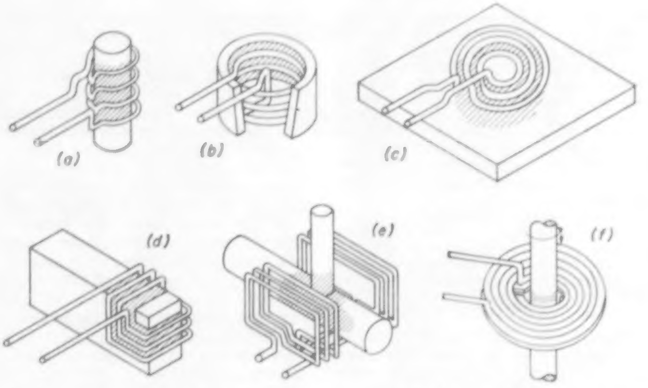

Fig. 2. Typical Work Coils or Inductors for Induction Heating Units

For through hardening and tempering, calculations based on the energy input per pound (kw-sec per lb) of metal heated are used extensively, since depths and patterns of hardness are not a problem. Estimates of power requirements on this basis are particularly common with 60-cycle induction heating. The energy input per pound varies with the temperature of heating; approximate values are 600 kw-sec per lb of steel (power as measured at the power line supply) for heating to 1600 to 1700 F, and 300 kw-sec per lb when heating to 1150 F for scanning operations. From such data the energy input per piece may be calculated and, as before, the power or size of the converter may be estimated from the amount of time available to heat each piece as determined from the production requirements.

Selection of Coil Design

The success of many induction heating applications is related to the selection and design of the proper work coil or inductor. This design is influenced by a number of factors, including the dimensions and configuration of the part to be heated, the heat pattern desired, whether the part is heated throughout its length at the same time or progressively, the number of parts to be heated at one time and the amount of power available.

The strength of the magnetic field within the inductor or work coil is the basic factor that determines the rate of heating. For most rapid heating rates, therefore, inductors are designed to provide the maximum flow of current in the inductor, and the closest coupling (distance between inductor ID and the part) permissible, after consideration of work handling features and arcing between the work and the coil. In practice, considerable variation exists in the design of coils for tube, spark-gap, motor-generator and line frequencies. At all frequencies, however, the coils are generally of copper, because of its high conductivity and wide availability at moderate cost. The copper may be in the form of tubing or solid bus bar, or a combination of both if required.

A number of basic work-coil designs for use with spark-gap and tube units and the heat patterns developed by each are shown in Fig. 2. These basic shapes include: *(a)* a simple solenoid for external heating, *(b)* a coil to be used internally for heating bores, *(c)* a "pancake" coil for spot heating, *(d)* a coil designed for brazing carbide tips to shanks, *(e)* a split-solenoid coil for heating tubing joints, and *(f)* a "pie-plate" type of coil designed to provide high current densities in a narrow band for scanning applications.

The basic shapes shown may, of course, be distorted to fit the contour of cam surfaces, gear teeth, cones and other irregular shapes. In addition, combination coils can be constructed to provide simultaneous heating on the inside and outside diameters, as well as multiple-section coils for heating several pieces at one time, conveyor-type coils and split coils of various designs. Solenoid-type coils for external heating are most efficient and should be used whenever possible.

Commercial copper tubing may be used for such coils. The tubing must be large enough to permit an adequate flow of water for cooling. With machines of very low power, the tubing may be as small as ⅛-in. diam but is usually 3/16 or ¼-in. diam for units of 20 to 50 kw. Tubing is frequently partially flattened to increase the number of turns per unit length. Once formed, the coil can be supported by fastening the individual turns to rigid strips of insulating material. If required, the turns of the coil may be insulated from each other or from the work, with close-fitting, flexible (spun) glass tubing or other insulating materials.

Coil turns are normally spaced 1/16 to 3/32 in. apart with a 1/16 to ⅛-in. space (coupling) between the workpiece and the coil. Considerable adjustment in the heat pattern is possible by varying either the spacing between turns or the coupling for individual turns.

The design of inductors for motor-generator frequencies may be considered in two categories: (1) a single-turn inductor for high current densities (20 to 50 times the generator output current) is employed to confine heating to a comparatively narrow band or segment, and (2) a multi-turn inductor for low current densities (1 to 5 times the generator output current) is employed to heat through the part or heat a wider or larger area. Single-turn inductors ordinarily utilize a stepdown transformer between them and the generator, while multi-turn inductors are connected to the generator either directly or through another transformer.

The thickness of the copper conductor used with motor-generator units is important. For efficient operation the following minimum thicknesses of wall may be used as a guide in constructing multiturn coils.

Minimum Wall Thickness, in.	Frequency, cycles per sec
0.120	1,000
0.070	3,000
0.040	10,000

Whenever possible in the construction of single-turn coils, where current densities may be considerably higher, these minimums should be increased three or four times.

A great many surface hardening applications lend themselves to the use of single-turn inductors of bus bar construction. Such an inductor for use at motor-generator frequencies is illustrated in Fig. 3. Because of the high current densities and the extremely thin cross section in which the current confines itself, artificial cooling is required. This is usually accomplished by circulating water through channels provided for the purpose. These channels may be made by drilling connecting holes or milling out a path to make a completed loop around the bore of the inductor, and then plugging the exposed ends of the holes or brazing a copper sheet over the milled passage to make a continuous watertight cooling channel. Cross-sectional areas of the cooling passages in the order of 0.060 to 0.125 sq in. will provide adequate cooling at water pressures of 40 to 50 psi for power inputs from 30 to 150 kw.

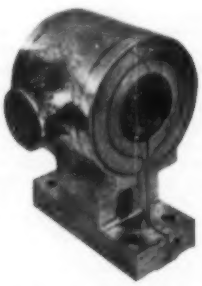

Fig. 3. Inductor Block for Heating and Quenching Cylindrical Bars. Brazed fabrication of solid bus bar.

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Often this design of inductor can include another water chamber with a suitable pattern or series of orifices directed for spray quenching the heated area. Such a spray quench is effective for "single-shot" hardening of work that is stationary while being heated and quenched. For progressive hardening of a narrow band or area, the orifices must be directed at an angle so that the quenching medium will strike the heated work as it moves out of the inductor. A satisfactory angle, which eliminates backwash of the quench, is about 30 deg from the work.

For hardening areas on cylindrical parts using a "single-shot" technique, the length of the inductor bore should be longer than the area to be hardened, the actual overlap decreasing with an increase in power density. With intermediate power densities the inductor bore should be approximately ⅝ in. larger than the area to be hardened if that area does not extend to the end of the part. If the area to be hardened is at the end of a shaft or protrudes from the shaft as on an eccentric, cam or gear, the inductor bore should be ¼ in. longer than the area. For efficient transfer of energy the inductor bore may be 0.120 to 0.200 in. larger in diameter than the part. As the bore is increased, the work will approach a weaker portion of the magnetic field, heating time will be increased, and the heated pattern will be deeper unless the power density is increased correspondingly.

With the cylindrical areas described, single-shot inductors are generally operated at power densities of 5 to 15 kw per sq in. When the length of the hardened area is such that the power density obtainable is lower than that required for a specified maximum case depth, it is logical to consider an inductor for progressive hardening, if the work is adaptable. The shorter inductor will usually permit the power density requirement to be satisfied. An inductor bore 1 in. long is satisfactory for shafts of ¾ to 3-in. diam, although the bore may be shorter if the power is limited.

Sometimes, for production reasons, it may be desired to harden more than one part at a time. If enough power is available and the shape of the part permits, the number of bores in the inductor may be increased accordingly, or multiple coils may be used.

To permit access in hardening a bearing on a part with a shape that cannot be threaded through the bore of the inductor, the inductor may be split in half and the two halves clamped together when carrying current. Good contact surfaces are mandatory and are usually made of coin-silver strips brazed to the inductor at the points of juncture.

In constructing inductor coils for heating irregular shapes, it should be remembered that the portions of the work closest to the inductor will usually be in a stronger magnetic field and will heat more rapidly. If the irregularity is in the transverse plane of the part and does not have sharp corners, thin sections, or sharp re-entrant surfaces, a hardness pattern generally following the contour of the part may be expected with a circular inductor. If this is not satisfactory, an inductor should be constructed with a uniform air gap so that the bore will follow the irregularity. It may still be found necessary to "relieve" or increase the air gap around the section having least mass, in order to reduce the strength of the magnetic field and reduce the heating rate. An example of this might be a cam or an automotive camshaft.

If the irregularity is in a longitudinal plane parallel to the axis of the inductor bore, as in a shaft with a bearing surface and an adjoining shoulder to be hardened, the inductor may again be machined initially to follow the shape of the part to produce a uniform air gap. The current density, however, will be the strongest at the smallest bore dimension, because the current will follow the path of least impedance; therefore it will be found necessary to increase the dimension of the air gap at this point in order to decrease the heating rate.

Another such example is in hardening the teeth and roots of a bevel gear. Here again the current density will be strongest at the smallest bore dimension, and it will be necessary to increase the air gap to the teeth at that point to produce a uniform hardening pattern.

The effect of the air gap on the hardness pattern produced for a number of irregular shapes is shown schematically in Fig. 4. In practice, it may be difficult to avoid overheating at sharp corners.

As with high-frequency coils, the coils constructed for line frequencies (60 cycles) are almost invariably made of copper tubing through which water is passed to maintain a safe working temperature. For an equivalent voltage many more turns are required in the low-frequency coils, but it is feasible to use multilayer construction.

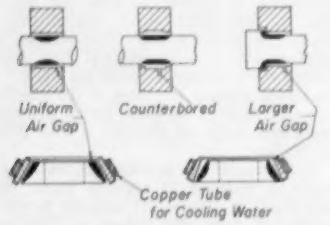


Fig. 4. Influence of Air Gap or Coupling on Heat Pattern

Optimum efficiency is usually achieved by keeping the radial dimensions of the tubing smaller than about 0.300 in. Rectangular tubing gives the best space factor and strongest construction. With the insulating and lining materials now available, it is practicable to build coils that are capable of operating up to 600 v.

Frequently it is necessary to compromise in the design of an inductor. Such a compromise is the inductor for the cam shown in Fig. 5. In this application the frequency was 1920 cycles. The cam was heated and quenched in a single-turn, round inductor. The lower frequency employed shows its influence in the relatively deep hardness pattern. In the tips of the cam the current followed the shortest possible path, thus eliminating the extreme tips, which probably were not heated by induction, but by conduction of heat from other parts of the cam. The sections of the cam nearest to the inductor show deeper hardening than the rest of the part. A more uniform pattern could be secured by using a shaped inductor and higher frequency; however, this example illustrates the results obtained from a simple round inductor shape when it is used with contoured parts.

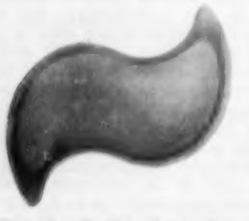


Fig. 5. Brake Cam Surface Hardened at Frequency of 1920 Cycles. Heated and quenched in single-turn, round inductor

Matching of Impedance

Efficient transfer of energy available from the high-frequency converter to the workpiece depends on good matching of impedance as well as on good coil design. This applies to all types of equipment for induction heating and is particularly important when work coils or inductors have low impedance (one and two turns). Matching equipment consists of auto-transformers, fixed-ratio stepdown transformers, variable-ratio stepdown transformers and capacitors.

Motor-Generator Units. Motor-generator units are rated according to maximum power, amperage and voltage. The maximum rated power cannot be attained unless the maximum ratings of amperage and voltage are reached at the same time. For example, a generator rated at 50 kw and 440 v would require 113 amp to secure maximum power. If a load were connected that would draw 60 amp at 440 v with a unity power factor, the actual power in kilowatts would be (60 × 440)/1000 or 26.4 kw—slightly more than half the 50 kw available. A load that drew 113 amp at 200 v with unity power factor would result in (113 × 200)/1000 or 22.6 kw. The 113-amp load prohibits the generator from using enough voltage to attain maximum rated power. In addition, single-turn inductors frequently used with motor-generator equipment have such low impedance that considerable capacitance must be provided for in the circuit in order to maintain a unity power factor.

The simplest but least flexible method of matching impedance is that of the fixed-ratio stepdown transformer with a capacitor bank between generator and inductor. This method is the least expensive and can be designed for a particular load, but only one type of load can be run at the rated power of the generator when properly matched. Other types of load may be run but at somewhat lower power. A more flexible method is to connect an autotransformer, capacitors and a fixed-ratio transformer between generator and inductor. This is most often used when the generator voltage is high (800 v) to permit the selection of a lower fixed-ratio stepdown transformer. It also has the advantage that it permits matching several different loads accurately, within limits, by changing taps on the autotransformer, provided the proper ratio is maintained at the fixed-ratio transformer.

Two other methods are similar to those mentioned above except that they employ variable-ratio rather than fixed-ratio stepdown transformers. In each of these methods considerably greater flexibility is attained, but at higher initial cost and slightly reduced operating efficiency.

Many variables obviously affect the ultimate selection of the transformer ratio for best matching of impedance in a given application. While no simple formulas are available for determining or selecting this ratio, certain basic observations derived from experience are helpful, for example:

1. As the length of the inductor increases, an *increase* in the number of turns on the primary of the transformer is necessary to maintain constant power and constant generator voltage and current.
2. As the diameter of the part increases, a *decrease* in the number of turns on the primary of the transformer is necessary to maintain constant power and constant generator voltage and current.
3. In order to draw the same power when inductors and parts of the same size and shape are involved, an increase in turns on the primary of the transformer will require a higher generator voltage, and vice versa.
4. With constant generator voltage and size and shape of inductor and part, a decrease in transformer ratio will increase the power and the amperage, and vice versa.
5. For a given generator voltage, and size and shape of inductor and part, an increase in frequency will require a decrease in transformer ratio, or vice versa, to maintain the same power.

Table IV may be used as a guide for estimating suitable transformer ratios for 10-kc equipment. Actual trials should be made to determine exact ratios because of great differences in characteristics of transformer, circuit and inductor. This table is for single-turn inductors, and it is assumed that the inductor is ⅜ in. longer than the hardened area and 3/16 in. larger in ID than the OD of the part. If Table IV is to be used for a specific set of variables not actually listed together, the five observations previously set forth may be applied for estimation. For example, if a 2-in. diam part is to be hardened over a 1⅛-in. length, the inductor would be ⅜-in. longer than the hardened length, or 1½ in. long. A transformer ratio of 9.5 to 1 is rec-

Table IV. Transformer Ratios for Impedance Matching in 10-Kc Equipment(a)

Inductor Length, in.	Power, kw	Transformer Ratio(b) 220 v	400 v	800 v
	½-In. Section Size			
½	10	26	....	....
1	20	19.5	....	....
1½	30	17.5	....	....
2	40	16.5	....	....
	¾-In. Section Size			
½	12.5	22	....	....
1	25	17.5	....	....
1½	37.5	15.5	....	....
2	50	14.5	....	....
	1-In. Section Size			
½	15	19.5	....	....
1	30	15.5	....	....
1½	45	14	25	....
2	60	13	23	....
2½	75	12	22	....
	1½-In. Section Size			
½	20	16.5	....	....
1	40	13	23	....
1½	60	11.5	20.5	....
2	80	10.5	19	....
3	100	10.5	19	....
	2-In. Section Size			
1	50	10.5	19	38
1½	75	9.5	17	34
2	100	8.5	16	32
3	150	8	14.5	28
	2½-In. Section Size			
1	50	10	17.5	35
2	100	8	14	28
3	150	7	13	26
4	200	6.5	12	24
	3-In. Section Size			
1	75	7	12.5	25
2	150	5.5	10	20
3	225	5	9	18
4	300	4.5	8	16
	4-In. Section Size			
1	100	....	9.5	19
2	200	....	7.5	15
3	300	....	6.5	13
4	400	....	6	12

(a) Single-turn inductors. (b) "26" means "26-to-1" transformer ratio, and so on.

ommended in Table IV for this operation to maintain 75 kw with a 220-v, 10-kc generator. If 50 rather than 75 kw were used for this same job, the observation made in item 4 of the preceding listing could be applied, and a ratio would be selected somewhat higher than 9.5 to 1 (12 to 1, for instance).

When multi-turn coils are used, the coil for large parts can often be designed so that no transformer is needed and load matching is accomplished by the usual complement of capacitors alone. In tests of loaded coil impedance, it is usual to check the impedance matching with the generator in operation and the work cold. Starting with a low value of capacitance, capacitors are added to the circuit to secure unity power factor with the maximum values of voltage or amperage within the rating of the generator. If the voltage is low but the current is high, the load impedance presented to the generator is not great enough and coil turns must be increased or the coil more loosely coupled to the load. If the current is low but the voltage is high, excessive impedance is indicated and better matching may be accomplished by removing coil turns or coupling more closely to the work.

If changes in coil design and capacitance do not result in full loading of the generator (rated voltage and amperage at unity power factor), then a transformer of the proper ratio is needed as with single-turn inductors. A combination that works well with multi-turn coils is the use of an autotransformer and capacitors as "matching" equipment. This method permits greater freedom in coil design since the autotransformer can be used to match the load with a range of selections in number of turns and tubing size.

Spark-Gap Units. Matching impedance in a spark-gap converter requires tuning the circuit in the machine to resonance with the output circuit. A variable inductance in the unit, controlled from the outside, may be adjusted to give a maximum reading on an output meter at the point where the best transfer of energy is attained. This adjustment can be made with the work hot or cold, depending on the power available and the amount of heat necessary in the work. The resonance setting is indicated on a numbered dial. Some work coils may show two resonance points as the tuning is varied. The correct setting is the one that gives the highest reading on the output meter. With coils of very low impedance (single-turn or small-diameter coils) suitable matching often is not possible with the variable inductance in the converter, consequently a transformer is required to obtain the matching.

As with motor-generator equipment, correct impedance matching is important. Incorrect resonance settings result in lower efficiency of power transfer to the work and in a longer heating time.

Tube Units. Matching impedance in tube units usually requires an output transformer with a primary winding of high impedance to match the high impedance in the tube output circuit. Secondary windings are usually 1, 2, 3, 4 or 5 turns, depending on the size of the heating coil and the work load. Voltage output increases with the increase in secondary turns in the transformer. Capacitors are sometimes used in the load circuits for certain applications to afford some measure of correction of the power factor, but must be chosen with care because of the higher voltages encountered in these circuits.

When heating coils of one or two turns are used with an output transformer, the coil leads must be kept as short and as close together as possible so that inductance in the leads is of low value. Widely spaced or long leads may have as much inductance as the heating coil itself and can result in waste of a large part of the power available from the transformer.

Influence of Temperature on Impedance Matching. Since the magnetic permeability and electrical resistivity of ferrous loads change as heating occurs, the impedance of the work circuit will change as the work temperature increases, so a perfect impedance match is impossible. If the impedance is matched while the work is cold, the demand for power will usually increase at first and then decrease as the work increases in temperature. This may be an advantage in avoiding overheating if sufficient power is available to continue heating at this stage of the heating cycle; but may be a disadvantage if limited power is available and the change results in loss of efficiency at higher temperatures.

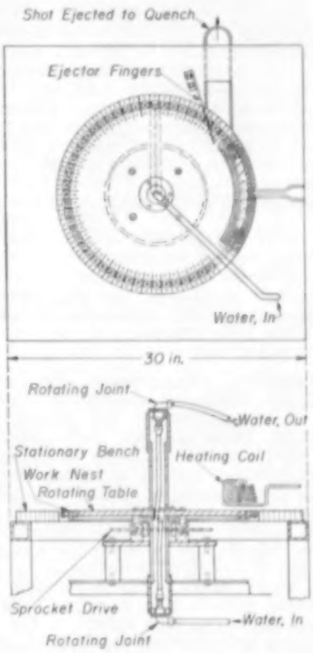


Fig. 6. Rotary Table and Conveyer Coil Arrangement for Continuously Hardening 20-mm Steel Shot

Matching the impedance with work that is hot will result in better transfer of energy at the higher temperatures but will cause slower initial heating of the cold work—or, with tube converters, overloading. The change of impedance as the work becomes heated may be partially compensated by the timed addition of capacitance or inductance to the output circuit.

Selection of Accessory Equipment

Integration of coil design, quench arrangement and fixtures, and handling equipment frequently allows induction heat treating operations in high speed production lines. On the other hand, manually operated or partially mechanized fixtures and work-handling arrangements are used successfully with minimum initial cost. While basic principles of machine design are applicable, special advice concerning materials of construction is desirable from equipment manufacturers or users. Aluminum, brass and nonmetallic materials are used frequently to minimize heat losses.

Work-Handling Equipment is available in a number of standard units. Typical arrangements include hopper and magazine feeding of small parts, or conveyer and rotary table feeding of larger parts to the work coil and thence into the quench. Often parts are rotated to provide greater uniformity of temperature.

A schematic drawing of a rotary table arrangement for continuously hardening 20-mm steel shot is shown in Fig. 6. In this installation, shot loaded at one location are moved continuously through a conveyer type of coil designed to provide the required heat pattern, and are quenched, after emerging from the coil, by dropping through an opening in the table into a quench tank.

Gears and other cylindrical parts may be moved by horizontal conveyers that stop at each station. Rotating spindles raise the piece into the inductor and quench, returning the piece to the conveyer carrier after treatment. The conveyer then moves on.

Vertical and horizontal scanning fixtures are often designed to provide rotation of the part, and controlled movement of the coil and quench arrangement along the part. Such fixtures normally have arrangements for surface hardening either the whole length or desired sections of the part. In one operation, differential pinion shafts are surface hardened continuously to a depth of 0.100 to 0.150 in. by dumping the shafts from tote pans into a hopper from which they are fed mechanically into a vertical slide or tube and into the inductor block. The travel of the shafts is controlled by rollers or guides, above and below the block, that cause the parts to rotate at about 100 rpm as they pass through the inductor and spray-quench ring. The heating time is controlled automatically as the work passes through the inductor, so that the specified length of the shaft is heated for hardening. After hardening, the shafts drop onto an incline and roll to a platform from which they are picked up and packed into a basket for tempering.

For selective hardening, parts are frequently heated in a multiple coil, which consists of two or more connected work coils. In such an arrangement one multiple-coil unit may be reloaded while a second unit goes through a hardening cycle. Upon completion of the heating cycle, parts are dropped into the quench automatically.

Integration with Machine Tools. The automation of induction heating equipment is only the first step in combining automatic machining operations with automatic induction heat treating. The multispindle automatic screw machine, the rotating-dial type of fixture for multispindle machining, the modern process line or transfer line and the common conveyer all offer possibilities for including automatic induction heating.

Parts machined in stages on automatic machines can be hardened on the same equipment. After machining the surface to be hardened, the tooling is arranged to include an inductor on one station. It is preferable to use the inductor alone on this station, but it may be combined with machine tooling on adjacent areas if necessary.

Figure 7 shows a schematic drawing of the arrangement used for induction hardening of the bore of a part made on an automatic screw machine under a patented process.

Several automatic machine tools may have hardening operations powered by a single generator or source of power. The machining time on station is usually several times the heating time. A typical cycle may be about 12 sec, which consists of 2-sec index time and 10-sec machining time. The heating time for small parts is usually from 1 to 3 sec. This allows ample time to stagger the heating cycles on several machines and thus use the power source more efficiently.

Automatic control equipment is interlocked electrically so that power is fed to only one inductor at a time, or to a predetermined number of inductors. As soon as the cycle for this group of inductors is completed, the power may be fed to the next set of inductors. This interferes in no way with the machining cycle.

The capacity of the power source is determined by the sum of the power required by the maximum number of inductors that may be connected at any one time. The inductor on each machine has its own timing circuit and interlocks; it is thus connected to the power source only when it is in position on the workpiece.

Special inductors are mounted on the tool slide but insulated electrically from it. The electrical insulation must withstand the action of the cutting fluid, which is also the quenching medium used in the machine. The design of inductors is about the same as would be used elsewhere. Heating of internal diameters usually requires a cylindrical inductor shaped to the contour of the bore if possible. The inductor is moved into and out of the part by action of the tool slide. A circular inductor may be used to surround the part if the part is short or the area to be hardened is near the outer end of the part. This is the most efficient type. When the area to be hardened is at a considerable distance from the end, a semicircular inductor is used, contoured to the shape of the part. This type of inductor is ordinarily mounted on a cross slide. Plastic or ceramic insulators and nonferrous metals should be used to minimize loss of power.

The source of power should be located as near the machine as possible. This may be accomplished by grouping the machines around the power source or by mounting the power source above or below the machines on a different floor level.

Conductor leads, from power source to machine, are of the usual design. Coaxial tubing is ideal for high frequencies (450,000 cycles), although copper bus bars may be used if spaced closely, flat and parallel. These must be guarded to protect personnel and shielded to prevent radiation interference. The coaxial tubing eliminates all radiation problems. Low-frequency power (9600 cycles or less) may be distributed by heavy, insulated copper cables, instead of bus bars or coaxial cable, if more convenient.

To connect the power leads to the inductor a transformer should be mounted as close to the inductor as possible. It should be constructed of materials that withstand the cutting lubricant. Insulation that resists both oil and water should be used throughout. The inductor and all transformer output leads should be water-cooled. Where design permits, the center tap of the transformer secondary should be grounded to reduce the voltage from the inductor to the ground.

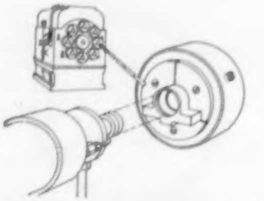


Fig. 7. Integration of Induction Hardening with Automatic Screw Machine

Quenching Arrangements. For most induction hardening applications water or oil is specified as the quenching medium. Brine and air (self-quench) are used occasionally. Since water provides greatest ease in handling, minimum installation of equipment and maintenance, and greatest safety, it is used unless metallurgical considerations indicate the necessity for one of the other quenching mediums.

A water spray applied through a separate quench ring or from hollow inductors of the type shown in Fig. 3 has been used successfully in most applications involving plain carbon and low-alloy constructional steels; oil is specified for steels of higher hardenability and parts with nonuniform sections where difficulty with cracking and distortion is anticipated. Quenching in water or oil may also be by submersion in an agitated bath or by a combination of a spray quench ring and submersion in a tank on completion of the heating cycle. Submersion in a brine tank may be specified for steels of very low hardenability to prevent occurrence of soft spots on the surface of the hardened part.

An air quench is frequently used with success to harden small areas of alloy steels selectively heated by induction. In such an air quench, the rate of cooling achieved by loss of heat to the surroundings and to the adjoining cold metal is sufficient to harden the heated area. An air quench may require compressed air applied through quench rings as with water or oil.

Quench water systems are usually separate from the cooling water supply for the induction heating unit, because it is desirable to have a wider range of temperature control and variable pressure control for different quenching arrangements. Public water supplies and deep wells or, if necessary, water recirculating systems with cooling towers are usually satisfactory. Recirculating systems consist of storage tanks, pumps and heat exchangers with adjustable control and are frequently protected with alarms and cutoffs for regulating pressure, temperature and flow. Pressures in water quenching vary from 30 to 85 psi; temperatures vary from 60 to 105 F.

Oil quenching systems likewise consist of storage tanks, pumps and heat exchangers for heating and cooling, with adjustable automatic control. Oil quench pressures vary from 30 to 90 psi; oil temperatures vary from 80 to 150 F, and the volume is designed for ample flow and agitation without foaming at the point of quench. Either propeller-type agitators or high-pressure flow from the oil supply will improve the efficiency of quenching. Ventilation is recommended for the removal of fumes, vapors and heat. The vaporized oil from a spray quench and from the immersion of large heated parts in oil creates a fire hazard; fire control systems that use carbon dioxide are recommended for combating flash fires. The hazard of fire can be reduced by the introduction of nitrogen around the part at the point of quenching.

Parts can be induction scanned and spray oil quenched without the use of nitrogen to counteract fire hazards, provided complete quenching is accomplished without vaporization of the oil. The limitations of this process vary with speed of scanning, amount of heat that must be removed from the heated part, oil pressure at the quench ring, angle of spray and the amount of oil flowing from the quench ring. In all instances, a heavy cascading flow of oil must completely cover the heated portion immediately below the inductor until the temperature of the quenched part is below the vaporization temperature of the quenching medium.

Arrangements for quenching in water or oil are generally integrated with the fixtures and handling equipment. In equipment for scanning, the quench ring and work coil or inductor move as a unit along the part. Obviously the distance between the coil and the quench ring determines the delay between heating and quenching and must be controlled. Where spray quenching is achieved through the inductor, the angle of spray is 30 to 50 deg away from the heated area, striking the piece to give full coverage without excess splashing and foaming. In hand-operated and semi-automatic fixtures, upon completion of the heating cycle the piece is quenched in a tank, either by hand or by automatic trip timed with the heating cycle.

Control Accessories

Charts or graphs, representing the relationship between depth of hardening and heating time for various power densities and for various steels, can often be used to obtain a reasonably accurate estimate of the required cycle. Other estimates can be made from results for similar parts or by careful observation of the part itself as it is heating. However, the final hardening cycle is generally determined by experimentation.

After a part has been hardened with one experimental arrangement, it is checked for hardness and examined for cracks. It is then sectioned with a rubber-bonded cutoff wheel, checked accurately for specified hardness at a given depth and prepared for a thorough examination of the microstructure. Should hardness, hardened depth or microstructure fail to meet desired standards, or if cracks are found, the cycle is adjusted accordingly and the process repeated until satisfactory results are obtained.

This procedure may be facilitated considerably with the aid of a high-speed recorder-controller and a thermocouple or special radiation devices available commercially. These units are designed to provide a minimum of inertia in response, and therefore to record and control with suitable accuracy the temperature at the surface of parts heated at normal speeds.

Once the hardening cycle has been determined, production control of the process is achieved by repetition of the experimental cycle automatically, with respect to heating time or temperature, power density, delay between heating and quenching, and the quenching cycle. In addition, parts are checked periodically by metallurgical examination for structure, case depth and hardness. The paragraphs under the four headings that follow include descriptions of equipment required to control each of these variables in a way that will insure depth of hardening accurate to within ±10% and suitable structure and hardness in a medium-carbon steel.

Heating Time. For parts heated in a fixed position relative to the inductor, a heating time of 10 sec or less should be controlled to within ±0.1 sec. For heating times greater than 10 sec but less than 60 sec, this control should be within ±0.2 sec, and for heating times of 60 sec or more, within ±1.0 sec.

A multiple-circuit timer of the synchronous motor-driven type, properly operated and maintained, will control the induction hardening process within the limits mentioned. A timer that is easily adjusted should be selected if the equipment is used for a variety of parts. For equipment requiring infrequent changes of time cycle a drum type of timer will serve as well.

For scanning operations the rate of travel of the part relative to the inductor should be controlled within ±1%. Electronic motor controls will effect tolerances within ±1% even though line voltages vary by ±5%. Oil hydraulic drives are reliable after the oil has warmed up to operating temperature, and a number of good variable-speed transmission drives are available.

Power Density. Uniform heating from part to part can be obtained only if the power density and the heating time are controlled carefully. For a given part, power density will be affected by the electrical characteristics of the high-frequency converter, line voltage variation, variation in coupling, and symmetry of the part.

A uniform density of power may be achieved with automatic voltage regulation of the source of power for the induction heating unit. With short heating cycles or large voltage fluctuations (±5%), greater uniformity of results justifies the cost of automatic voltage regulators. When it is intended to cut one or more loads in and out of the circuit while heating others, automatic voltage regulation should always be used. In such an application it is necessary to keep the load well balanced in order to get uniform results. Rotating and electronic voltage regulators are available that will control the line voltage within ±1%.

To secure consistent results constant coupling is necessary in induction hardening. For a given part and coil, the coupling will be determined primarily by the ability of the fixture to position the part consistently to provide a constant air gap between the coil and the part. Some variation in coupling can be tolerated when the inductor completely surrounds the workpiece by one or more turns. For face heating with a pancake-type coil or modifications thereof, the coupling is critical, and should be maintained within 1/64 in. if a highly restricted hardness pattern is required.

If the part to be hardened is of irregular size and shape, uneven heating will result because of nonuniform power density. While many of these parts can be hardened successfully, it is very difficult and often impossible to maintain a hardened depth within ±10%.

Delay Time. The delay time for single-shot operations is the interval between the time when the power is turned off and the time when the quenching medium contacts the workpiece. The delay is controlled easily by using an additional circuit of the same timer that controls the heating cycle. However, in the arrangement of quench lines and manifold, variation should be avoided in the time lapse between the opening of the quench valve and the striking of the quench medium on the part. When the volume of the quench is small, solenoid-operated valves work satisfactorily, but when quench lines are larger than 3 in. particular care should be taken to select a quench valve that will open and close quickly and that will be trouble-free and uniform in operation.

For scanning operations the delay time is a function of the rate of travel and the distance between the inductor and the point where the quenching medium makes contact with the part. Here again the equipment used to regulate the rate of travel for heating is accurate enough for reproducing the delay time.

Quenching Cycle. Successful control of the quenching cycle involves accurate control of the quenching time, the temperature of the quenching medium and, in spray quenching, the quenching pressure, velocity and direction. The quenching pressure should be measured as close to the discharge orifice as possible, and a standard dial type of pressure gage may be used for this purpose. A standard valve may be employed to regulate the pressure of the quenching medium.

One circuit of a multiple timer used to control the heat cycle will generally control the quench cycle with sufficient accuracy. Some industrial plants utilize the residual heat in the part (not quenching the part to the temperature of the quenching medium) to make subsequent tempering unnecessary. This practice requires careful control of quenching time for uniform results.

Maintenance of Equipment

Induction hardening equipment is expensive and generally it is impossible to provide standby equipment. A preventive maintenance program is therefore imperative, and availability of certain critical parts for ready replacement is highly desirable. Since induction hardening equipment seems complex to the average mechanic, a special training program and permanently assigned personnel will reduce the cost of maintenance.

Dust, dirt, moisture and high ambient temperatures are the primary causes for failure in electrical equipment, and one or all of these conditions are usually present in industrial locations where induction heating units are installed. In addition, cooling with air or water is necessary for almost all induction heating units, and some problems develop in regard to suitable water-cooling systems.

The volume, pressure and temperature of water supplied for the cooling of tube, spark-gap or motor-generator units should be controlled within certain limits. Meters or gages are used to indicate these limits, and high and low-pressure switches, flow switches, and temperature-controlled switches act to stop operation of the induction heating unit if the preset limits are exceeded.

Often water from public supplies or deep wells may be used directly with a storage tank to stabilize the temperature. However, where water conservation is important or control of water temperature is necessary to avoid condensation of water, recirculating systems with cooling towers are used. The water-cooling system should have adequate volume to give uniform control of both heating and cooling and may be supplied with filters to remove metallic particles and sludge. Where water hardness exceeds 10 to 12 grains per gal, the water must be treated by water-softening chemicals or water-softening equipment.

Salt or acid additives that decrease the electrical resistance of the water should be avoided. Some manufacturers of tube units specify the use of distilled cooling water to provide a minimum resistivity of 5,000 to 10,000 ohm-cm. This standard can be met by a commercial grade of double-distilled water. Under such circumstances, it is advisable to install a recirculating distilled water system.

For equipment that is air-cooled, building air is normally satisfactory. In locations where air temperatures exceed 100 F at certain seasons of the year, it is necessary to provide cooling equipment, usually by piping air from a cooler location through a bank of filters.

Maintenance of Motor-Generator Equipment. The following specific items should receive periodic attention to assure continuous operation with minimum cost:

1 Clean or change air filters periodically to maintain sufficient cool, clean air for air-cooled generators.
2 Inspect for accumulation of dirt on windings and in air gap of motor generator units installed in dirty locations, and arrange for periodic cleaning to forestall breakdown of insulation.
3 Check insulation resistance of motor and generator windings periodically.

4 Check air gap periodically to determine wear of bearings in units with sleeve bearings.
5 Oil or grease bearings periodically; always follow manufacturer's recommendations exactly as to method and grade of lubricant.
6 Maintain recommended volume and temperature of water through water-cooled generators, capacitors, transformer windings and inductors.
7 Clean or replace timer, relay and line contactor contacts periodically.
8 Clean capacitor bushings and inspect for water leaks.
9 Automatic timing devices of the mechanical type are made up of many small moving parts that should be kept clean and oiled sparingly.

Maintenance of Tube and Spark-Gap Equipment requires preventive measures as follow:

1 Clean or change air filters periodically to insure that sufficient cool, clean air is available for air-cooled oscillator tubes, rectifiers or spark gaps.
2 Maintain recommended volume and temperature of water through water-cooled oscillator tubes or spark gaps.
3 Clean capacitor bushings and other high-voltage insulators and terminals to prevent arc-over.
4 Inspect for water leaks.
5 To avoid condensation, which can become a problem, cooling water should be recirculated through a heat exchanger and water temperature should be maintained above dew point.
6 Clean or replace timer, relay and line contactor contacts periodically.
7 Maintain spark-gap spacing regularly according to manufacturer's recommendation.

General. Inductors that are changed often for various applications should have the contact surfaces cleaned frequently. Also, the slot between transmission leads must be kept free from scale or metallic deposits to prevent arcing that eventually would burn a hole in the inductor.

Where quenching is by spray, the plugging of quench orifices with foreign material can cause soft spots in the quenched object. Adequate filtering and frequent inspection can prevent this difficulty.

Selection and Control of Material

The heating and quenching operations in induction hardening are concerned with the formation and decomposition of austenite in the same general way as are other hardening methods. However, induction heating differs from other heat treating in two important respects: (1) it heats the metal very rapidly and (2) it usually involves zero holding time at the hardening temperature. These factors provide a minimum of time for metallurgical reactions and have a significant influence on the selection of steel, prior microstructure, and hardening or austenitizing temperature.

Short austenitizing times may also have a significant influence on the hardness, structure, residual stress pattern and distortion.

Selection of Steel for Induction Hardening. Medium-carbon steels are generally specified for induction surface hardening; the most common by far are 1045 and 1050. These grades, which can be induction hardened readily to minimum hardnesses of Rockwell C 58 and 60, respectively, are less susceptible to cracking than steels of higher carbon content. Also, they can be water-quenched, have a desirable combination of properties in the unhardened core, and are relatively inexpensive. These two grades of steel should be among the first studied in the selection of a steel for surface hardening.

However, all ferrous metals containing enough combined carbon can be induction hardened successfully. Some suitable materials are given in Table V. The list given should be considered indicative rather than all-inclusive. Available free-machining grades and alloy grades with equivalent carbon contents are often specified.

Table V. Recommended Induction Hardening Temperatures and Minimum Surface Hardnesses for Various Metals(a)

Metal	Hardening Temp, deg Fahr	Quench	Rc Min(b)
	Carbon and Alloy Steels(c)		
0.30% C	1650 to 1700	Water	50
0.35 ...	1650	Water	52
0.40 ...	1600 to 1650	Water	55
0.45 ...	1600 to 1650	Water	58
0.50 ...	1600	Water	60
0.60 ...	1550 to 1600	Water or Oil	64 or 62
>0.60 ...	1500 to 1550	Water or Oil	64 or 62
	Cast Irons(d)		
Gray Iron Pearlitic	1600 to 1700	Water	45
Malleable	1600 to 1700	Water	48
Nodular	1650 to 1700	Water	50
	Stainless Steel(e)		
Type 420	2000 to 2100	Oil or Air	50

(a) Metals listed in this tabulation are typical of those successfully induction hardened and the listing is indicative rather than inclusive.

(b) Minimum surface hardness, Rockwell C. See Fig. 11 for hardnesses possible and ordinarily obtainable with water quenched steels of all carbon contents.

(c) Free-machining and alloy grades with equivalent carbon contents may be induction hardened. Alloy steels containing carbide-forming elements (chromium, molybdenum, vanadium or tungsten) should be heated 100 to 200 F above the temperatures indicated.

(d) Combined carbon should be 0.40 to 0.50% min; hardness will vary with amount of combined carbon present.

(e) Other martensitic grades of stainless steel, types 410, 416 and 440, have been induction hardened.

When induction surface hardening replaces case hardening by carburizing, a change to a higher-carbon steel is usually imperative to attain suitable surface hardness. Furthermore, plain carbon steels frequently replace alloy steels, since hardenability is not a problem in surface hardening to normal depths by induction. Attention should be given to any change caused in core properties by the change in steel.

Two examples illustrate changes in steel to allow successful induction hardening:

1 Pins used in the track assemblies for crawler tractors were previously made of 1018 steel and case hardened by carburizing; these pins are now made of 1049 steel surface hardened by induction with a substantial reduction in the cost of processing as well as an improvement in the quality of the heat treated product.
2 Final drive gears for large tractors were formerly made from 2345 steel, permitting an oil quench to minimize distortion. However, even this mild quench was not slow enough to eliminate the distortion problem. Consequently the hardened gears were tempered to a compromise hardness of Rockwell C 40 and finish machined to required dimensional tolerances — a sequence of operations that increased the cost considerably. A change to 1043 steel, induction hardened selectively and tempered to Rockwell C 50 to 55 after finish machining, resulted not only in substantial reductions in the costs of steel and processing but in improvement in wear resistance because of the higher hardness, and in greater fatigue resistance produced by resultant compressive stresses at the surface of the treated steel.

Where parts must be machined extensively before induction hardening, the free-machining grades C1137 and C1144 are frequently specified.

Alloy steels of medium carbon content may also be hardened by induction heating and are required if high core properties are specified in relatively large sections to be surface hardened or when through hardening is required. The procedure for selection of these alloy steels is similar to that given in the 1954 Supplement to the Metals Handbook, in the article on pages 1 to 20-F, since selection is based on hardenability criteria.

Steels such as 4145, 4150, 5145, 5160, 6145 and 6150, which contain carbide-forming elements (Cr, Mo and V), behave sluggishly and require either higher hardening temperatures or longer heating cycles to achieve solution of carbide and the normal effects of the alloying elements. Steels containing smaller amounts of carbide-forming elements, such as 8645 or 8650 are often surface hardened with minor adjustments in the induction hardening cycle, while steels, such as 2345, containing noncarbide-forming elements, are induction hardened with the same ease as plain carbon steels. Provided suitable hardness is obtained, the presence of considerable amounts of undissolved carbides appears to have no detrimental effect.

Cast Irons may vary significantly in combined carbon content, and results from induction hardening are nonuniform unless control is established over the combined carbon content. A minimum combined carbon content of 0.40 to 0.50% C (as pearlite) is recommended for gray iron castings to be hardened by induction. Heating castings with lower combined carbon content to high hardening temperatures for relatively long periods of time may dissolve some free graphite, but such a procedure may coarsen the grain structure at the surface and results in larger amounts of retained austenite in the surface layers.

Selection of Prior Structure

The microstructure of the steel before induction hardening is important in selecting the heating cycle to be used. Steels most readily hardened have carbides that are small and uniformly dispersed, as obtained by quenching and tempering. Such structures are readily austenitized. Accordingly, minimum case depths can be developed with maximum surface hardness while using very rapid rates of heating.

Pearlite-ferrite structures, typical of normalized, hot rolled and annealed steels containing 0.40 to 0.50% C, also respond successfully to induction hardening. Much of the steel that is induction hardened has such structures. The actual distribution and size of the ferrite and carbide in these structures varies considerably; the pearlite becomes coarser and the ferrite more massive as the cooling rate is decreased. Likewise a decrease in carbon content increases the amount of ferrite. Thus it becomes more difficult to obtain homogeneous austenite before quenching annealed steels unless higher austenitizing temperatures or longer heating times are used. With either alternative, greater case depths are to be expected.

Figure 8 shows the effect of prior microstructure on the response of a 1050 steel to induction hardening. The data shown represent the time and temperature required when heating for hardening to achieve maximum hardness in the steel after quenching: (1) for a furnace-cooled structure containing a considerable amount of free ferrite and coarse pearlite, and (2) for a quenched and tempered structure containing a fine and uniform dispersion of carbide in ferrite (tempered at 930 F). The tempered martensite structure responds more readily, but an increase in austenitizing temperature provides suitable response in the furnace cooled structure also.

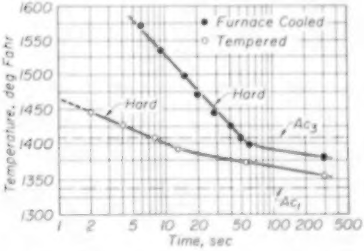


Fig. 8. Effect of Prior Microstructure on Response of 1050 Steel to Induction Hardening. Curves show minimum austenitizing for full surface hardness after quenching from the temperatures indicated. (D. L. Martin and M. C. Van Note)

Steels containing more than 0.50% C are frequently spheroidized for improved machinability. Such spheroidized structures have the poorest response to induction hardening; the larger the carbide particles, the poorer the response. Coarsely spheroidized structures may require hardening temperatures 300 F or more above the transformation temperature to redissolve the carbide and obtain uniform hardening results. Such high temperatures at the surface may lead to coarse austenitic grain size, coarse martensitic structures and significant quantities of retained austenite, which may be detrimental to fatigue resistance and may promote galling or seizing.

When a coarsely spheroidized structure is encountered in production, parts may be run through the hardening cycle twice to achieve maximum surface hardness at a sacrifice of production time and minimum distortion. Figures 9(*a*) and (*b*) are micrographs of the prior structures for kingpins made of 1050 steel. Showing a fine pearlitic structure typical of normalizing, the steel in Fig. 9(*a*) had excellent response to hardening. The steel in Fig. 9(*b*), showing a spheroidized structure, was run through the hardening cycle twice to provide satisfactory results rather than to increase the surface temperature.

Selection of Hardening Temperature

Table V gives recommended hardening temperatures for a number of steels commonly hardened by induction. For plain carbon steels and steels containing noncarbide-forming alloying elements, exhibiting a suitable prior structure, temperatures 50 F higher than those used in furnace hardening are suitable, as indicated. This higher temperature compensates for the very short heating times.

When carbide-forming elements (Cr, Mo, V, W) are present in constructional steels, it may be necessary to raise the hardening temperatures 100 to 200 F above those shown in Table V for equivalent carbon contents. The exact increase in temperature depends on the length of the heating cycle, the specific alloying elements present, the specific effects desired from the alloying elements, and the surface hardness required. These higher temperatures at the surface are used to obtain adequate solution of the carbon and alloying elements in the austenite with very short heating cycles. As the heating cycle is lengthened to produce deep cases or through heating, hardening temperatures should approach those given in the table.

With the usual induction hardening cycles, the hardening temperatures given in Table V will produce a fine austenitic grain size. This also applies to steels that contain carbide-forming elements heated 100 to 200 F higher to provide alloy solution, since the alloy carbides inhibit austenitic grain growth as long as they remain undissolved. With longer heating cycles, there is danger of grain coarsening if the temperature is not reduced. Figure 10 illustrates the influence of temperature and time on austenitic grain growth in a 1050 and a 6150 steel. An ASTM or fracture grain size of 6 or finer is specified for most parts hardened by induction heating.

In addition to grain coarsening, excessive hardening temperatures in induction heating may result in pronounced distortion and cracking. If specifications call for close limits of case depth and hardness pattern, overheating may also cause failure to meet specifications, actual through-hardening of thin sections, or possibly hardening into a critical area where machining or drilling is yet to be done. With pronounced overheating and long heating cycles, surface scaling may be encountered.

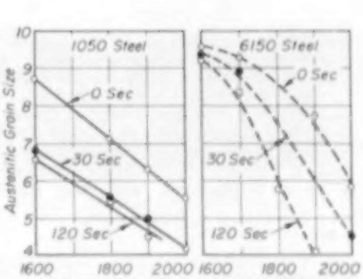


Fig. 10. Influence of Induction Hardening Temperature and Time on Austenitic Grain Size in 1050 and 6150 Steels

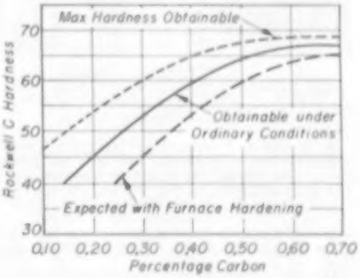


Fig. 11. Relation Between Hardness and Carbon Content of Water Quenched Steels. Upper two curves for induction heated steels, bottom curve for furnace heating (R. H. Lauderdale)

Control of Surface Hardness

Table V presents minimum values for surface hardness frequently specified in commercial induction hardening. The minimum values are given to avoid needlessly close hardness specifications and correspondingly close control and high cost. Considerable variation in the hardness of the cast irons may be expected because of a variation in the combined carbon content.

As shown in Fig. 11, the hardness obtained on a given part may be sev-

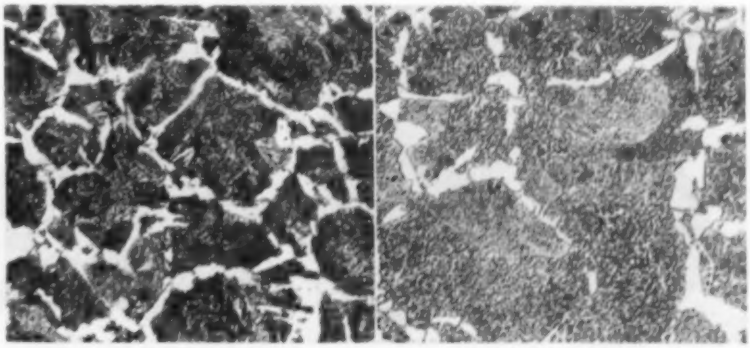
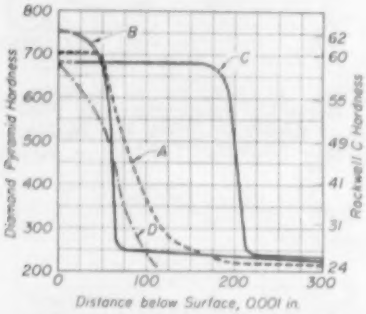

(*a*) Readily Hardened (*b*) Unsatisfactory Response

Fig. 9. Effect of Prior Microstructure on Hardening of 1050 Steel. × 500

eral points Rockwell C higher than the minimum values recommended in Table V. It is also apparent from Fig. 11 that the maximum hardness obtained in surface hardening by induction is usually higher than that obtained by hardening the same steel from a furnace. This higher hardness is most pronounced with the short heating cycles characteristic of parts that are *surface* hardened and disappears in parts through hardened or surface hardened to produce a deep case.



A is for a 1⅞-in. diam spindle, progressively hardened. 400 kc, 50 kw, 1045 steel, water spray quench

B corresponds to Fig. 13(a). 10 kc, 16 kw per sq in., 2-sec heating time; 5140 steel

C corresponds to Fig. 13(b). 10 kc, 10 kw per sq in., 5-sec heating time; 5140 steel

D is for pearlitic malleable iron. 10 kc, 75 kw per sq in., 1½-sec heating time, water spray quench

Fig. 12. Depth-Hardness Curves for Some Parts Surface Hardened by Induction

Low hardness at the surface after induction hardening may be the result of a number of factors. A few contributing factors are listed below:

1 Lower carbon content than specified, possibly as a result of surface decarburization *before* induction hardening. The usual induction hardening operations do not cause measurable decarburization because of the short time of heating.

2 Inadequate heating temperature or time, or both. Inadequate solution of carbon in the austenite before quenching will result in low hardness. Steels with unsuitable prior structures and alloy steels containing carbide-forming elements are most susceptible to low hardness from this source. Nonuniform performance of the induction heating unit and timer may also cause difficulty.

3 Unsatisfactory quenching conditions. Hot water or cold oil may result in low or spotty hardness, as will low pressures of either water or oil. Orifices in the quenching equipment that are plugged because of inadequate filtering may cause the same conditions.

Control of Case Depth and Contour

Hardness patterns on induction hardened parts are normally revealed by sectioning the piece with an abrasive wheel under water, rough grinding on a belt, polishing on fine emery paper, and then etching with a 2 or 5% nital solution until the pattern develops. The case depth is frequently reported as the depth from the surface at which the hardness drops below Rockwell C 50, although in initial studies for a given part, complete depth-hardness curves and microscopic analysis of the fully hardened and transition zones of the case are recommended. Figures 12 and 13 show depth-hardness curves and macroscopic analyses for parts hardened by induction.

Basically, the depth of the hardened case obtained by induction heating followed by a suitable quench depends on the frequency, the power density, the heating time and the steel. In addition, the hardness pattern or contour depends on the shape of the part as related to coil design. The following illustrations may serve to relate these factors. (The influence and control of each factor have already been discussed in preceding sections.)

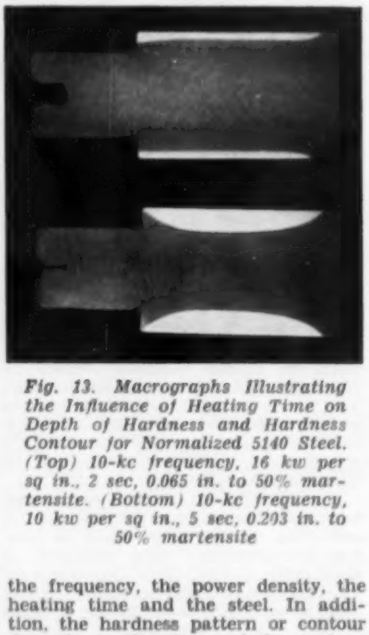


Fig. 13. Macrographs Illustrating the Influence of Heating Time on Depth of Hardness and Hardness Contour for Normalized 5140 Steel. (Top) 10-kc frequency, 16 kw per sq in., 2 sec, 0.065 in. to 50% martensite. (Bottom) 10-kc frequency, 10 kw per sq in., 5 sec, 0.203 in. to 50% martensite

Minimum depths of case are produced by using high frequencies, short heating times as determined by high power densities, close coupling and efficient matching, and a quenched and tempered prior structure. This is illustrated by a study of Table II. The data in column 3 of Table VI are presented as a guide to the minimum practicable depths of hardness possible at various frequencies, using high power density (15 kw per sq in. min) and an optimum prior structure and type of steel. In practice, the depths of hardness associated with each frequency are generally greater than the minimum shown, and column 4 of Table VI presents a guide for the practicable working depths of hardness using medium power densities (5 to 15 kw per sq in.) and steel in the as-rolled or as-forged condition. Greater case depths may be obtained at each frequency by increasing the time of heating and decreasing the power density.

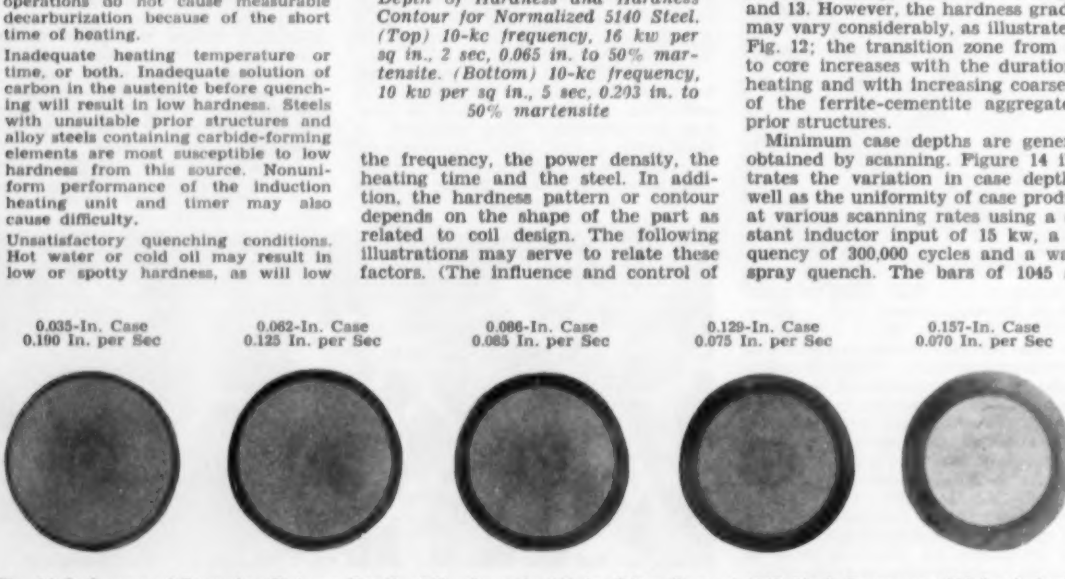
Table VI. Effect of Frequency on Depth of Case Hardness

Frequency, cycles per sec	Theoretical Depths of Penetration (Approximate) of Electrical Energy,[a] in.	Practical Depths of Case Hardness, in. Minimum[b]	Practical Depths of Case Hardness, in. Working[c]
1,000	0.059	0.100	....
3,000	0.035	0.060	0.150 to 0.200
10,000	0.020	0.040	0.100 to 0.150
120,000	0.006	0.030	....
500,000	0.003	0.020	0.040 to 0.080
1,000,000	0.002	0.010	....

(a) Effective initial penetration (time = 0). (b) For high power densities (15 kw per sq in. min) and optimum prior structure. (c) For medium power densities (5 to 15 kw per sq in.) and steel in the as-rolled condition.

With suitable prior structures, short heating times, and rapid quenching, the transition zone from case to core is generally sharp, as shown in Fig. 12 and 13. However, the hardness gradient may vary considerably, as illustrated in Fig. 12; the transition zone from case to core increases with the duration of heating and with increasing coarseness of the ferrite-cementite aggregate in prior structures.

Minimum case depths are generally obtained by scanning. Figure 14 illustrates the variation in case depth as well as the uniformity of case produced at various scanning rates using a constant inductor input of 15 kw, a frequency of 300,000 cycles and a water-spray quench. The bars of 1045 steel



0.035-In. Case 0.190 In. per Sec

0.062-In. Case 0.125 In. per Sec

0.086-In. Case 0.085 In. per Sec

0.129-In. Case 0.075 In. per Sec

0.157-In. Case 0.070 In. per Sec

Fig. 14. Influence of Scanning Rate on Depth of Hardness in 1⅛ in. Diam Bars of 1045 Steel. Frequency 300 kc, inductor input 15 kw. Case depth and scanning rate (in. per sec) shown above each macrograph

Fig. 15. Distortion of Hardness Pattern at Ends of Inductor

Fig. 16. Nonuniform Hardness Pattern at End of Spline

for this example were of 1⅛-in. diam.

Figures 15 and 16 illustrate the nonuniformity that may occur in the hardness pattern even in symmetrically disposed pieces. The pattern in Fig. 15 is associated with the greater inefficiency of the inductor at its ends as compared with the center. Often this pattern is not objectionable. However, if a uniform depth of hardness is necessary within a specified length of shaft, a closely coupled coil with an increased air gap at the center (see Fig. 4) may change the pattern so that it is approximately the same depth for the length of the inductor.

Similar effects can be obtained in the use of a multi-turn coil by increasing the inside diameter of the center turns of the coil or increasing the spacing between turns at the center of the coil. The increased depth of case at the end of the spline shown in Fig. 16 is caused by overheating at the end as the coil passes. Since the heat loss to the cold section of the bar does not take place at the end, the input of energy is greater and the case deeper. If objectionable, this condition may be minimized by accelerating the scanning rate at the end of the piece.

With some scanning controls it may be impossible to accelerate at specific locations. In such applications, the power may be reduced or cut off before objectionable overheating occurs.

The shape of the part may also have a significant influence on the heat pattern. Parts with nonuniform cross section do not develop a uniform pattern, since edges and corners heat to a higher temperature. The effect of a change in cross section, illustrated in Fig. 17, is exaggerated at higher frequencies. Though changes in the design of inductor may compensate for the distortion caused in the heat pattern by small changes in shape, if a uniform case depth is required, complex parts are difficult if not unsuitable for induction surface hardening.

Some variations of the heat patterns produced in nonuniform sections are shown by the macrographs of gears, a spline and a lead screw in Fig. 18; Fig. 18(*a*) represents an attempt to provide "contour hardening" on gear teeth, that is, high hardness on the surface of the teeth and at the root, while maintaining a soft core in the tooth. With a uniform heating time and a uniform metallurgical structure, higher frequencies accentuate contour hardening. Because of this fact, gears—particularly larger gears—can be preheated using lower frequencies (60 or 10,000 cycles), and then the heating can be completed with frequencies of 200,000 to 500,000 cycles. Figure 18(*b*) shows the pattern produced on a transmission gear by preheating at 10,000 cycles and then heating at 210,000 cycles. Contour hardening of the root and tooth profile develops compressive prestress as well as hardness at the surface, thus providing good resistance to fatigue and wear while the unhardened core imparts toughness to the gear.

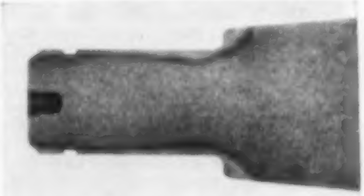


Fig. 17. Distortion of Hardness Pattern Caused by Variation in Size of Section

In the hardening of gears, however, even frequencies of 500,000 cycles may fail to provide contour hardening of the teeth when the pitch is 5 or finer. Under such conditions the hardness pattern extends through the tooth and below the root circle as shown in Fig. 18 (*c*) for a spiral gear and 18(*d*) for a spline shaft. While such contours are suitable for many applications involving improved wear with light loads, they are not recommended for heavy or shock loads.

A further modification of the hardness pattern on the teeth of a lead screw is shown in Fig. 18(*e*). In this instance the pattern extends across the tooth and below the pitch line, thus providing resistance to wear at the pitch line, but does not extend below the root. Such a pattern allows straightening after surface hardening

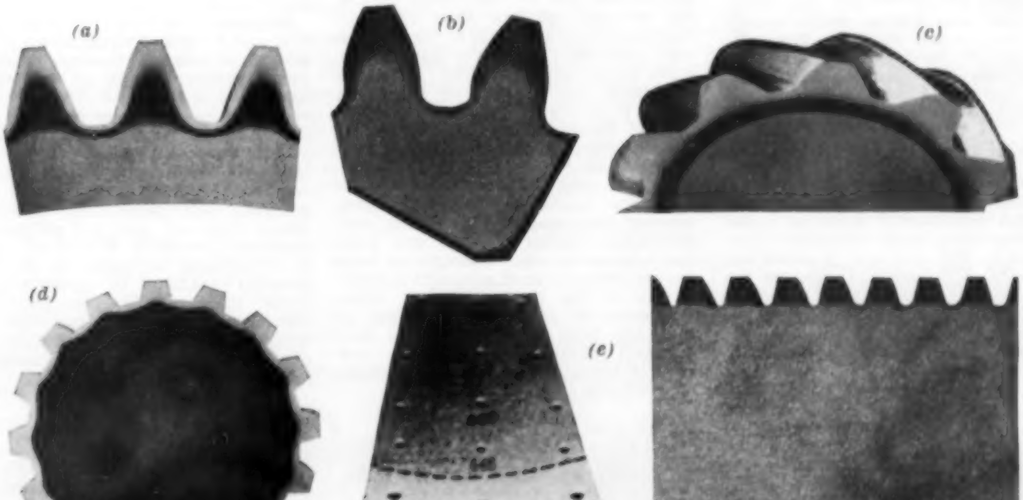


Fig. 18. Variation in Hardness Patterns for Gear Teeth and Screw Threads. (a) Contour hardening, (b) partial contour resulting from 10-kc preheating and 210-kc final heating, (c) spiral gear induction hardened below root circle, (d) spline hardened below root circle, (e) lead screw induction hardened below pitch line but above root circle

to provide extreme precision, if required.

In large gears or splines with a coarse pitch, unique hardness patterns are sometimes obtained *not* by controlling the heated contour but as a result of the combined influence of the hardenability of the steel and the severity of quench on the through heated gear teeth.

Control Limits

Needlessly close control can incur added costs in steel, equipment and labor. The necessity for such control can start when the engineer specifies hardness depths and patterns that may be satisfactory for the design and service of the hardened part but which place unnecessary or even impracticable limitations on the size and frequency of the equipment, the tooling, fixtures, and even the steel itself.

A hypothetical example of the influence of close specifications on the choice of equipment and processing procedure might be a specification for a bearing surface on a 1-in. diam axle for a hardened area 1.50 in. long, plus 0.060 and minus 0, and 0.030 to 0.040 in. deep with a minimum surface hardness of Rockwell C 58. The induction hardening equipment required would be a 50-kw, 500-kc converter; the fixture, if automatic, would have to position the work to within 0.030 in.; the steel should have prior heat treatment such as normalizing or quenching and tempering to respond to the short heating time required. If the service of the part would permit relaxing the specifications to a hardened area 1.50 in. long, plus 0.120 and minus 0, and 0.040 to 0.080 in., or even 0.100 to 0.150 in. deep, with surface hardness of Rockwell C 58 min, alternate equipment for this application would be a 50-kw, 10-kc motor-generator unit. With either type of equipment the cost would be reduced considerably, since the steel could be induction hardened "as rolled", thus eliminating the preliminary heat treatment, and the fixture would require positioning to only ±0.060 in. The operation would require less setup time, would need less precision in adjustment, and would be easier to inspect and control.

Residual Stresses and Distortion

Steel parts that have been surface hardened by induction generally exhibit less total distortion or more controlled distortion than parts quenched from a furnace. The decrease in distortion is a result of the support given by the rigid, unheated core metal, and of uniform, individual handling during heating and quenching. In scanning, distortion is controlled further by heating and quenching only a narrow band of the steel at one time. Unless a part through hardened by induction is scanned, the distortion encountered will approach that experienced in furnace hardening.

Selective heating of the surface, followed by quenching, produces residual stresses in the part. The balance between the kind of stresses developed may be somewhat complex, since they result from both rapid heating and subsequent quenching. However, this balance normally provides compressive stresses at the surface, tension at the juncture of the case and core, and compression in the core. This is shown in Fig. 19 for an induction hardened and tempered crankpin of a crankshaft analyzed for residual stresses by the Sachs boring out method. The diameter of the crankpin was 2⅝ in. and the length of the induction hardened surface 1 13/16 in. The steel was approximately 1052 (1.35% Mn). Before induction hardening, the hardness of the surface was 345 Bhn, while that of the core was 230 Bhn. After induction hardening, the hardness at the surface was Rockwell C 62 while that of the core remained unchanged. Induction hardening was followed by tempering at 400 F for 2½ hr, which lowered the surface hardness to Rockwell C 57 without changing the core hardness.

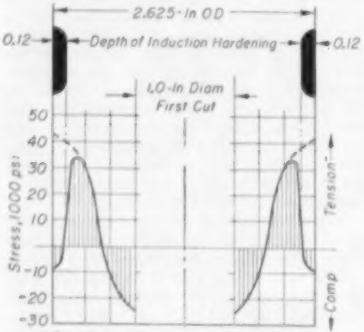


Fig. 19. Residual Stress Distribution in the Crankpin of an Induction Hardened and Tempered Production Crankshaft (W. G. Johnson)

The stress distribution shown in Fig. 19 is the result of localized plastic deformation resulting from nonuniform thermal expansion during heating, and contraction during cooling; and from the increase in volume associated with the transformation of austenite to martensite in the hardened layer. Consideration of these factors makes it apparent that the actual stress distribution obtained depends on the time of heating, the depth of hardening, and the steel itself.

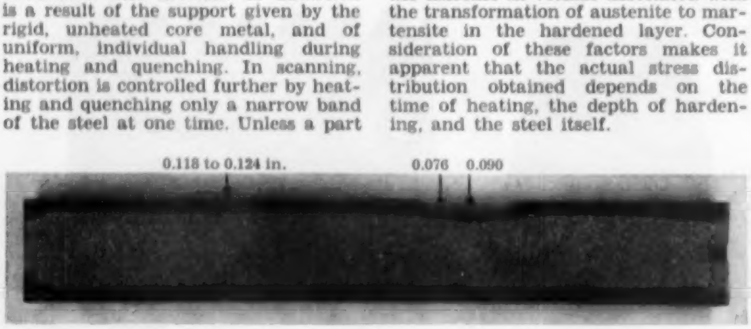
Compressive residual stress at the surface of an induction hardened steering knuckle pivot had a favorable influence on fatigue resistance, as shown in Fig. 20. For this part, induction hardening to an equivalent case depth provided fatigue resistance superior to case hardening by carburizing. Apparently, increased case depth further improved the fatigue resistance in this part. It is important to note, however, that high tensile stresses may exist at the juncture of case and core (Fig. 19). If the heat pattern brings the high-tensile zone to the surface in an area such as a fillet that is subject to repeated stresses, early fatigue failure may result. In addition, fatigue failure may occur at the juncture of the case and core.

Those medium-carbon steels most commonly used in induction hardening (0.40 to 0.50% C) do not exhibit cracking or spalling of the case when quenched from hardening temperatures that provide a fine austenitic grain size. However, quench cracks have been observed in induction hardened steels of more than 0.80% C. Also spalling may occur at the ends of shafts hardened progressively. Such spalling may be traced to excessive temperatures at the end heated last, with consequently coarse austenitic grain size.

Through Hardening by Induction

The induction process offers many of the same advantages for through hardening that it does for surface hardening. Some of these advantages are improved working conditions, saving of labor, reduced floor space, practical installation into the machine line, improved quality of the product, and adaptability to automation. One outstanding feature of through hardening by induction is adaptability to the scanning method, permitting heat treatment of bars, flats and other suitable shapes in mill lengths.

Previous comments concerning selection and control of equipment and steel provide a basis for through hardening by induction as well as for surface hardening by induction. Through hardening, however, requires a much larger source of power because of the greater volume of metal heated. Since large power installations decrease in cost with decreasing frequency, it is generally advantageous to select the lowest frequency that will perform the operation efficiently (1 to 10 kc). Since it is desirable to minimize the temperature gradient in through-heated parts, the lower frequencies are a further advantage. However, with sections smaller than 0.5-in. diam, frequencies of 300 to 500 kc are necessary for efficient heating (Table III).



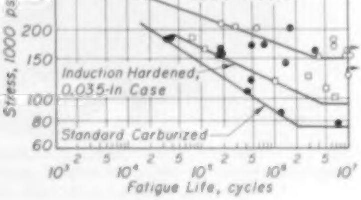


Fig. 20. (Right) Results of Fatigue Tests on Steering Knuckle Pivots Surface Hardened by Induction; (Above) Longitudinal Section with Typical Hardness Pattern and Case Depth at Critical Areas

information memo from the engineering laboratories of CONSOLIDATED VACUUM CORPORATION

CVC

Volume 1 Number 2

HIGH-VACUUM FURNACE DESIGN

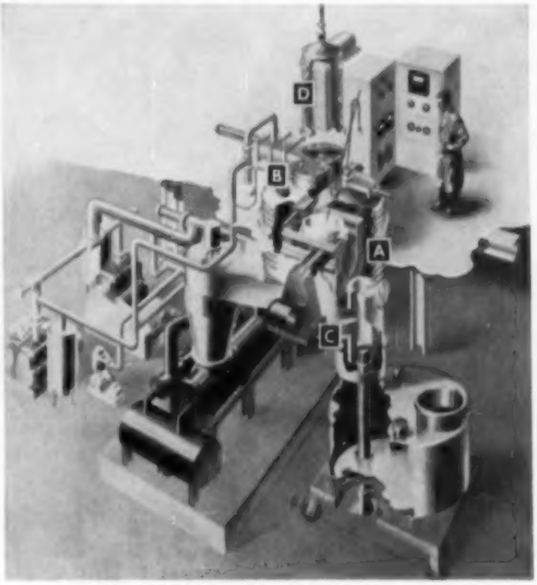
The module concept

"Building blocks" give high-vacuum furnaces flexibility.

CVC engineers are using the module concept in the design of high-vacuum metallurgical furnaces. This involves the construction of a series of component assemblies which can be interworked to meet initial requirements as well as changing or expanding needs.

These "building blocks" solve one of the most important problems facing potential users of high-vacuum furnaces—the fear of tying up capital in equipment for today's needs which might not meet the market demands a few years hence.

Presented with a module design like the one described here, buyers can plan their installations to meet present requirements while allowing for economical expansion to fill greater or even different needs in the future.



This installation implements all the basic modules discussed in the text. It is used for true semi-continuous melting and casting.

A Center chamber section and vacuum pumping system.

B Cover with control and inspection devices.

C Chamber bottom with multiple mold and interlock. Ram, which emerges from the floor, is moving the mold up to pouring position.

D Charging interlock with pre-heating induction coil.

A The basic design block

around which all variations are made is the center chamber section.

This basic portion of the furnace remains the same through all the variations provided by the different modules. The crucible-coil assembly is contained here. Since these vary in capacity depending on the nature of the application, the trunion supports of the center section are designed to accommodate the largest size. Thus, the user can increase the capacity of his melts simply by installing a larger crucible.

The pumping system is connected to this block through ports in the side of the chamber. There is room for one, two, or three of these ports depending on the pumping capacity desired. If a user requires only one pump in his initial operation, the other ports are blanked-off with steel plates which are easily cut out when additional pumping is needed.

B The chamber cover

contains the devices used in the control and inspection of the furnace contents.

The cover normally contains the alloying turret, bridge-breaking mechanism, a sampler, and the opening or connections used for pyrometers and other instruments. All are located within easy access of the operator.

The chief merit of all these assemblies is the fact that they are conveniently located for easy maintenance, and such items as the alloy-turret, and sampler, can be removed for servicing or cleaning *without disturbing the pressure within the chamber*. Valves and connections with the main pumping system make this possible.

C Different chamber bottoms

permit variation of casting techniques.

There are four basic designs for the furnace bottom: for casting single molds per vacuum cycle, for multiple molds, for centrifugal casting, and for semi-continuous operation. In addition to the flexibility of casting technique offered by interchangeable bottoms, they also facilitate cleaning of the chamber and simplify repairs in the event of spill-outs.

The buyer of one of these furnaces through a choice of different chamber bottoms can institute alternative casting methods as required.

D Interlocks

easily convert batch operation to semi-continuous production.

Semi-continuous operation is provided by adding interlocks through which the crucible can be charged, the alloying elements altered or adjusted, and the ingots or castings removed. The operator can accomplish all of these without breaking vacuum in the furnace.

Since these interlocks are accessory items, they can be added to the top and bottom sections as desired by initially providing flanges to accommodate them.

Tremendous leeway in planning for future as well as present needs results from this "building block" or module concept of high-vacuum furnace design.

Another great advantage is that damaged or obsolete parts can be replaced with little down time, at small cost.

If you would like more detailed information about the module concept in vacuum furnace design or information about any phase of vacuum metallurgy, contact **Consolidated Vacuum Corporation, Rochester 3, N. Y.** (a subsidiary of Consolidated Engineering Corporation, Pasadena, California). Reprints of this and other *information memos* in this series are available on request.

Consolidated Vacuum Corporation, **ROCHESTER 3, N. Y.**

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A.I.S.I. Standard Alloy Steel Compositions (a)

A.I.S.I. List Revised
February, 1954

Openhearth and Electric Furnace Alloy Steels

(Bars, billets, blooms and slabs up to 200 sq.in., 18 in. wide or 10,000 lb.)

A.I.S.I. Number *(b)*	C	Mn	Ni	Cr	Mo
1330	0.28-0.33	1.60-1.90	....	....	....
1335	0.33-0.38	1.60-1.90	....	....	....
1340	0.38-0.43	1.60-1.90	....	....	....
1345	0.43-0.48	1.60-1.90	....	....	....
2317	0.15-0.20	0.40-0.60	3.25-3.75	....	....
2515	0.12-0.17	0.40-0.60	4.75-5.25	....	....
E2517 *(c)*	0.15-0.20	0.45-0.60	4.75-5.25	....	....
3120	0.17-0.22	0.60-0.80	1.10-1.40	0.55-0.75	....
3130	0.28-0.33	0.60-0.80	1.10-1.40	0.55-0.75	....
3135	0.33-0.38	0.60-0.80	1.10-1.40	0.55-0.75	....
3140	0.38-0.43	0.70-0.90	1.10-1.40	0.55-0.75	....
E3310 *(c)*	0.08-0.13	0.45-0.60	3.25-3.75	1.40-1.75	....
E3316 *(c)*	0.14-0.19	0.45-0.60	3.25-3.75	1.40-1.75	....
TS4012	0.09-0.14	0.75-1.00	....	....	0.15-0.25
4023	0.20-0.25	0.70-0.90	....	....	0.20-0.30
4024 *(d)*	0.20-0.25	0.70-0.90	....	....	0.20-0.30
4027	0.25-0.30	0.70-0.90	....	....	0.20-0.30
4028 *(d)*	0.25-0.30	0.70-0.90	....	....	0.20-0.30
4032	0.30-0.35	0.70-0.90	....	....	0.20-0.30
4037	0.35-0.40	0.70-0.90	....	....	0.20-0.30
4042	0.40-0.45	0.70-0.90	....	....	0.20-0.30
4047	0.45-0.50	0.70-0.90	....	....	0.20-0.30
4053	0.50-0.56	0.75-1.00	....	....	0.20-0.30
4063	0.60-0.67	0.75-1.00	....	....	0.20-0.30
4068	0.63-0.70	0.75-1.00	....	....	0.20-0.30
4118	0.18-0.23	0.70-0.90	....	0.40-0.60	0.08-0.15
4130	0.28-0.33	0.40-0.60	....	0.80-1.10	0.15-0.25
TS4130	0.28-0.33	0.45-0.65	....	0.90-1.20	0.08-0.15
TS4132	0.30-0.35	0.45-0.65	....	0.90-1.20	0.08-0.15
4135	0.33-0.38	0.70-0.90	....	0.80-1.10	0.15-0.25
4137	0.35-0.40	0.70-0.90	....	0.80-1.10	0.15-0.25
TS4137	0.35-0.40	0.75-1.00	....	0.90-1.20	0.08-0.15
4140	0.38-0.43	0.75-1.00	....	0.80-1.10	0.15-0.25
TS4140	0.38-0.43	0.80-1.05	....	0.90-1.20	0.08-0.15
4142	0.40-0.45	0.75-1.00	....	0.80-1.10	0.15-0.25
TS4142	0.40-0.45	0.80-1.05	....	0.90-1.20	0.08-0.15
4145	0.43-0.48	0.75-1.00	....	0.80-1.10	0.15-0.25
TS4145	0.43-0.48	0.80-1.05	....	0.90-1.20	0.08-0.15
4147	0.45-0.50	0.75-1.00	....	0.80-1.10	0.15-0.25
4150	0.48-0.53	0.75-1.00	....	0.80-1.10	0.15-0.25
TS4150	0.48-0.53	0.80-1.05	....	0.90-1.20	0.08-0.15
4320	0.17-0.22	0.45-0.65	1.65-2.00	0.40-0.60	0.20-0.30
4337 *(e)*	0.35-0.40	0.60-0.80	1.65-2.00	0.70-0.90	0.20-0.30
4340	0.38-0.43	0.60-0.80	1.65-2.00	0.70-0.90	0.20-0.30
E4340	0.38-0.43	0.65-0.85	1.65-2.00	0.70-0.90	0.20-0.30
4608 *(f)*	0.06-0.11	0.25-0.45	1.40-1.75	....	0.15-0.25
4615	0.13-0.18	0.45-0.65	1.65-2.00	....	0.20-0.30
4617	0.15-0.20	0.45-0.65	1.65-2.00	....	0.20-0.30
4620	0.17-0.22	0.45-0.65	1.65-2.00	....	0.20-0.30
X4620	0.18-0.23	0.50-0.70	1.65-2.00	....	0.20-0.30
4621	0.18-0.23	0.70-0.90	1.65-2.00	....	0.20-0.30
4640	0.38-0.43	0.60-0.80	1.65-2.00	....	0.20-0.30
TS4720	0.17-0.22	0.50-0.70	0.90-1.20	0.35-0.55	0.15-0.25
4812	0.10-0.15	0.40-0.60	3.25-3.75	....	0.20-0.30
4815	0.13-0.18	0.40-0.60	3.25-3.75	....	0.20-0.30
4817	0.15-0.20	0.40-0.60	3.25-3.75	....	0.20-0.30
4820	0.18-0.23	0.50-0.70	3.25-3.75	....	0.20-0.30
5015	0.12-0.17	0.30-0.50	....	0.30-0.50	....
5046	0.43-0.50	0.75-1.00	....	0.20-0.35	....
5117	0.15-0.20	0.70-0.90	....	0.70-0.90	....
5120	0.17-0.22	0.70-0.90	....	0.70-0.90	....
5130	0.28-0.33	0.70-0.90	....	0.80-1.10	....
5132	0.30-0.35	0.60-0.80	....	0.75-1.00	....
5135	0.33-0.38	0.60-0.80	....	0.80-1.05	....
5140	0.38-0.43	0.70-0.90	....	0.70-0.90	....
5145	0.43-0.48	0.70-0.90	....	0.70-0.90	....
5147	0.45-0.52	0.70-0.95	....	0.85-1.15	....
5150	0.48-0.53	0.70-0.90	....	0.70-0.90	....
5152	0.48-0.55	0.70-0.90	....	0.90-1.20	....
5155	0.50-0.60	0.70-0.90	....	0.70-0.90	....
5160	0.55-0.65	0.75-1.00	....	0.70-0.90	....
E50100	0.95-1.10	0.25-0.45	....	0.40-0.60	....
E51100	0.95-1.10	0.25-0.45	....	0.90-1.15	....
E52100	0.95-1.10	0.25-0.45	....	1.30-1.60	....
6117	0.15-0.20	0.70-0.90	....	0.70-0.90	0.10 min. V
6120	0.17-0.22	0.70-0.90	....	0.70-0.90	0.10 min. V
6145	0.43-0.48	0.70-0.90	....	0.80-1.10	0.15 min. V
6150	0.48-0.53	0.70-0.90	....	0.80-1.10	0.15 min. V
TS8115	0.13-0.18	0.70-0.90	0.20-0.40	0.30-0.50	0.08-0.15
TS8117	0.15-0.20	0.70-0.90	0.20-0.40	0.30-0.50	0.08-0.15
TS8120	0.18-0.23	0.70-0.90	0.20-0.40	0.30-0.50	0.08-0.15
TS8122	0.20-0.25	0.70-0.90	0.20-0.40	0.30-0.50	0.08-0.15
TS8123 *(d)*	0.20-0.25	0.70-0.90	0.20-0.40	0.30-0.50	0.08-0.15
TS8125	0.23-0.28	0.70-0.90	0.20-0.40	0.30-0.50	0.08-0.15
TS8126 *(d)*	0.23-0.28	0.70-0.90	0.20-0.40	0.30-0.50	0.08-0.15
TS8127	0.25-0.30	0.70-0.90	0.20-0.40	0.30-0.50	0.08-0.15
TS8128 *(d)*	0.25-0.30	0.70-0.90	0.20-0.40	0.30-0.50	0.08-0.15
8615	0.13-0.18	0.70-0.90	0.40-0.70	0.40-0.60	0.15-0.25
TS8615	0.13-0.18	0.70-0.90	0.30-0.60	0.55-0.75	0.08-0.15
8617	0.15-0.20	0.70-0.90	0.40-0.70	0.40-0.60	0.15-0.25
TS8617	0.15-0.20	0.70-0.90	0.30-0.60	0.55-0.75	0.08-0.15
8620	0.18-0.23	0.70-0.90	0.40-0.70	0.40-0.60	0.15-0.25
TS8620	0.18-0.23	0.70-0.90	0.30-0.60	0.55-0.75	0.08-0.15
8622	0.20-0.25	0.70-0.90	0.40-0.70	0.40-0.60	0.15-0.25
TS8622	0.20-0.25	0.70-0.90	0.30-0.60	0.55-0.75	0.08-0.15
8625	0.23-0.28	0.70-0.90	0.40-0.70	0.40-0.60	0.15-0.25
TS8625	0.23-0.28	0.70-0.90	0.30-0.60	0.55-0.75	0.08-0.15
8627	0.25-0.30	0.70-0.90	0.40-0.70	0.40-0.60	0.15-0.25
TS8627	0.25-0.30	0.70-0.90	0.30-0.60	0.55-0.75	0.08-0.15
8630	0.28-0.33	0.70-0.90	0.40-0.70	0.40-0.60	0.15-0.25
8635	0.33-0.38	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
8637	0.35-0.40	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
8640	0.38-0.43	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
8641 *(d)*	0.38-0.43	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
8642	0.40-0.45	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
8645	0.43-0.48	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
86B45 *(h)*	0.43-0.48	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
8650	0.48-0.53	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
8653	0.50-0.56	0.75-1.00	0.40-0.70	0.50-0.80	0.15-0.25
8655	0.50-0.60	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
8660	0.55-0.65	0.75-1.00	0.40-0.70	0.40-0.60	0.15-0.25
8715	0.13-0.18	0.70-0.90	0.40-0.70	0.40-0.60	0.20-0.30
8717	0.15-0.20	0.70-0.90	0.40-0.70	0.40-0.60	0.20-0.30
8720	0.18-0.23	0.70-0.90	0.40-0.70	0.40-0.60	0.20-0.30
8735	0.33-0.38	0.75-1.00	0.40-0.70	0.40-0.60	0.20-0.30
8740	0.38-0.43	0.75-1.00	0.40-0.70	0.40-0.60	0.20-0.30
8742	0.40-0.45	0.75-1.00	0.40-0.70	0.40-0.60	0.20-0.30
8750	0.48-0.53	0.75-1.00	0.40-0.70	0.40-0.60	0.20-0.30
9255 *(g)*	0.50-0.60	0.70-0.95	....	....	....
9260 *(g)*	0.55-0.65	0.70-1.00	....	....	....
9261 *(g)*	0.55-0.65	0.75-1.00	....	0.10-0.25	....
9262 *(g)*	0.55-0.65	0.75-1.00	....	0.25-0.40	....
E9310	0.08-0.13	0.45-0.65	3.00-3.50	1.00-1.40	0.08-0.15
E9314	0.11-0.17	0.40-0.70	3.00-3.50	1.00-1.40	0.08-0.15
9840	0.38-0.43	0.70-0.90	0.85-1.15	0.70-0.90	0.20-0.30
9845	0.43-0.48	0.70-0.90	0.85-1.15	0.70-0.90	0.20-0.30
9850	0.48-0.53	0.70-0.90	0.85-1.15	0.70-0.90	0.20-0.30

Note *(a)* — All chemical ranges and limits are subject to the standard variations for check analysis over or under specification.

Note *(b)* — Numbers with prefix E are generally made in basic electric furnaces and unless otherwise noted the following specifications hold: Phosphorus 0.025% max., sulphur 0.025% max., silicon 0.20 to 0.35%.

Numbers without letter prefix are ordinarily made in basic openhearth furnaces and unless otherwise noted the following specifications hold: Phosphorus 0.040% max., sulphur 0.040% max., silicon 0.20 to 0.35%.

Specification limits for the acid electric and acid openhearth processes are: Phosphorus 0.050% max., sulphur 0.050% max., silicon 0.15 to 0.35%.

In all processes the maximum allowable quantities of unspecified and incidental elements are as follows: 0.35% copper, 0.25% nickel, 0.20% chromium and 0.06% molybdenum.

Numbers with prefix TS represent tentative standards designed to conserve strategic alloys.

Note *(c)* — When this steel is made in openhearth furnaces the manganese is 0.40 to 0.60%.

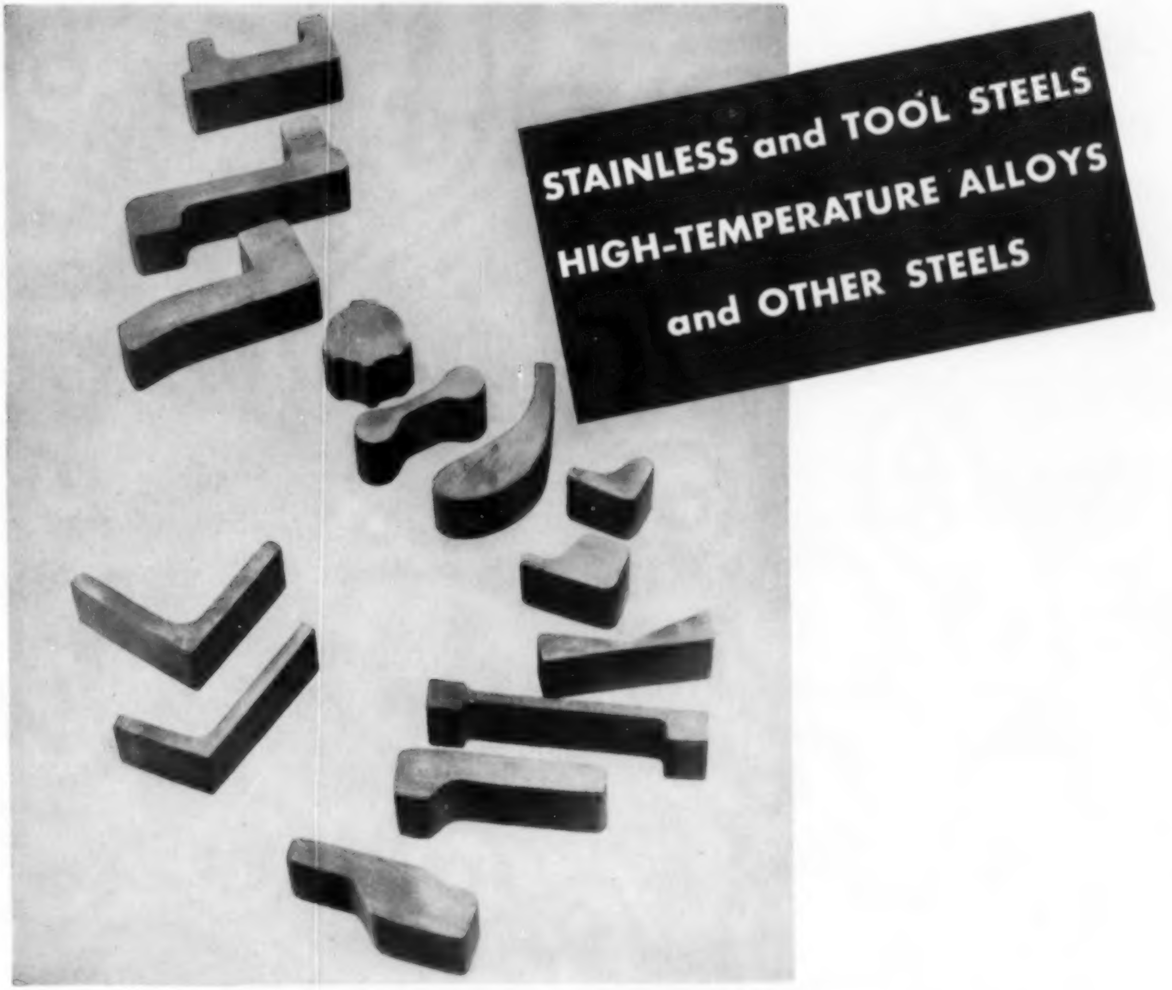
Note *(d)* — Resulphurized steels; sulphur is 0.035 to 0.050% except in 8641 where it is 0.040 to 0.060%.

Note *(e)* — When this steel is made in electric furnaces the manganese is 0.65 to 0.85%.

Note *(f)* — Silicon is 0.25% max.

Note *(g)* — Silico-manganese steels; silicon range is 1.80 to 2.20%.

Note *(h)* — This steel can be expected to have 0.0005% min. boron.



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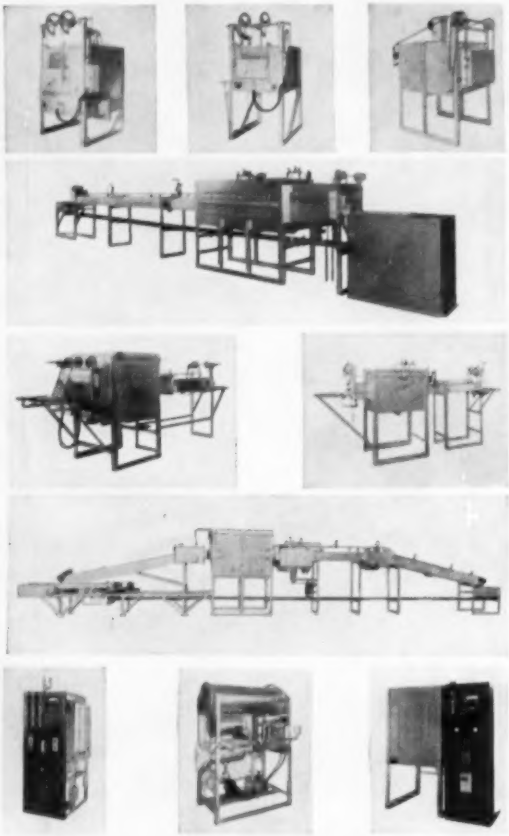

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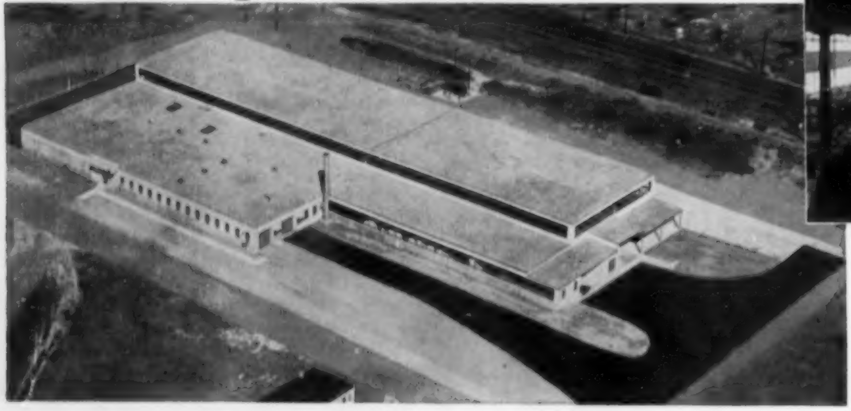

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Because of the great difference in heating rates, the choice of steel has considerably more influence on the efficiency of through heating by induction than on the efficiency of furnace heating. At a rate of heating normal for some induction heating applications certain steels will not form homogeneous austenite at the regular hardening temperature. These steels usually require heating to higher temperatures and thus result in fewer pounds of metal heated per kilowatt-hour of energy applied.

An example of through heating by induction is the integration of hardening and tempering inductors in the heat treating of mill lengths of bar stock. In this process the bar lengths are progressively moved by form rollers through an inductor coil and are sprayed with a high-pressure quench as they emerge from the coil. Continuing to advance on rollers, the bars pass through a tempering coil a short distance away. Twenty-foot bars of ½ to 1¾-in. diam that have been heat treated in this manner usually reveal less than 1 in. of distortion in their entire length. Bars of 1035 steel of ⅞-in. diam can be induction hardened consistently to a center hardness of Rockwell C 48. Bars of TS14B35 steel of 1¼-in. diam will harden by the same method to Rockwell C 48 at the center.

Figure 21 shows typical results of a Rockwell C hardness survey on a hardened cross section of 1¼-in. diam TS14B35 bar stock.

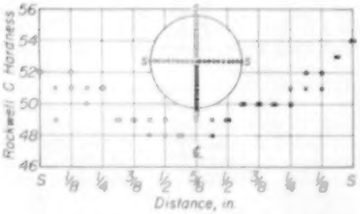

Fig. 21. Typical Hardness Survey on 1¼-In. Diam Bar of TS14B35 Steel Through Hardened by Induction

Flats and many other uniform shapes can also be through hardened by induction. Table VII contains data compiled from actual installations of high-production items.

Cost Relations

When considering cost relations, the applications of induction hardening may be placed in two categories: (1) where induction hardening provides a unique solution and cost is a secondary consideration; (2) where induction heating competes with other heat treating methods and cost is of paramount interest. There are some parts for which induction hardening is neither suitable nor competitive in cost.

Many selective hardening applications that require a restricted hardness pattern or a specified hardness gradient fall into the first category. A good illustration is the selective hardening of the inside edges of the claws of a claw hammer to avoid localized deformation, Fig. 22. In this instance, the primary consideration is for increased quality and service versus the cost of an extra operation, rather than for the cost of competitive methods. Localized induction hardening has been specified increasingly to avoid the necessity for compromises in the mechanical properties of a given part. The hardness gradient produced in 20-mm steel shot, Fig. 22, by proper coil design illustrates another unique application of induction hardening.

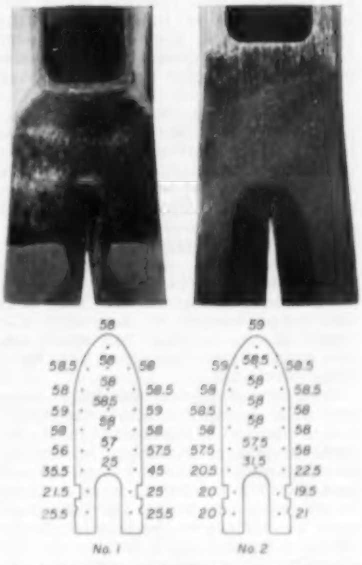

Fig. 22. Hardness Patterns Uniquely Suited to Induction Hardening. (Top) Highly restricted pattern on internal edges of claws for a claw hammer. (Below) Hardness gradient in 20-mm steel shot

Irregularly shaped parts that must be surface hardened to provide a uniform shallow case depth are not suitable for induction surface hardening regardless of cost. In addition, complex parts which require over-all hardening or through heat treatment to improve mechanical properties, and which lend themselves to bulk or volume handling, are generally better treated by other methods.

A typical example where induction could not compete with other methods is in hardening a tractor steering arm that consists essentially of one or two arms joined to a hub. In this instance 1045 steel is required, heat treated throughout to 240 to 286 Bhn. The part can be heated in a furnace to 1550 F for 45 min, water quenched and then tempered at 1025 F for 1 hr. Parts can be handled in batches, shoveled into the furnace, raked out into the quench and handled in baskets during tempering. In contrast, to heat this part uniformly by induction would require an inductor carefully constructed to bring the arms up to the same temperature as the hub. This would probably mean slow heating of one piece or a few pieces at a time.

In many instances induction hardening is competitive with other heat treating methods. The selection of induction hardening must then be justified on the basis of less cost per piece, considering all factors. The article entitled "The Cost of Heat Treating" (page 128 in the 1954 Supplement of the ASM Handbook) may be used as a helpful guide in arriving at cost estimates. In developing cost estimates for comparison of other surface hardening methods with induction surface hardening, it is particularly important to recognize that a change in type of steel is involved and that this may alter significantly the cost of operations other than actual heat treatment.

In large production operations, where induction hardening is competitive, it has proved economical for straight shafts, external surfaces that require selective hardening, and spur gears. However, other heat treating methods have proved more economical for bevel and helical gears. Where quantities are small, as in commercial heat treating, it is often difficult to justify the high initial costs of induction heating equipment and fixtures, and frequently induction hardening is used only when other heat treating methods would produce excessive distortion, scale or decarburization, or when special metallurgical or mechanical properties are required.

Induction Tempering

In the past five or six years extensive production experience with thousands of tons of steel per month has demonstrated the commercial success of induction tempering for many applications. Metallurgically, the success of induction tempering has been related fundamentally to the possibility of compensating for short tempering times with higher tempering temperatures. Economically, induction tempering has proved particularly adaptable to automation in production lines.

At present two principal areas of application exist for induction tempering: (1) selective tempering and (2) progressive tempering of bar stock previously hardened by scanning.

Many machine parts vary from one

Table VII. Data for Induction Through Hardening of Medium Carbon Steels (0.35 to 0.45% C)[(a)]

Section Size, in.	Frequency, cycles	Heating Time,[(b)] sec	Austenitizing Temp,[(c)] deg Fahr	Production,[(d)] lb per kw-hr	Inductor Input, kw per sq in.
½ (round)	9600	18.8	1750	4.81	1.11
⅝ (flat)	3000	15.2	1700	10.32	1.30
⅞ (flat)	3000	36.0	1700	7.50	1.11
⅞ (round)	9600	44.5	1750	6.33	0.66
1¼ (round)	9600	103	1750	5.75	0.42
1¾ (round)	9600	154	1750	7.14	0.32
½ to 1 (irregular)	3000	30	1700	7.92	1.00

(a) Hardened progressively. (b) Total time (t) as determined from length of inductor (l) and rate of feed (r), $t = l/r$. (c) Measured at surface of bar. (d) Power in kw was measured at power line supply.

section to another with respect to the load and wear requirements. Often this variation in requirements is met by a compromise of properties obtained by uniform tempering to a single hardness level. However, it is apparent that superior performance might be expected if the mechanical properties could be adjusted to meet the particular requirements in each section by selective tempering. Within certain limitations, induction tempering is an economical means of accomplishing this. These limitations are that the parts must be of such a shape and size that they can be coupled by the inductor to heat uniformly to the desired temperature in critical sections. Although this is impossible or impracticable for some parts, many can be tempered by induction selectively to obtain different degrees of hardness in the same part with a consequent improvement in quality.

Induction tempering is particularly applicable to bar stock previously hardened by induction. Symmetrically shaped parts (rounds, hexagons and tubing, for instance) are readily heat treated to uniform desired properties on a production basis by induction hardening and tempering. As in hardening, induction tempering of bar stock is accomplished by scanning.

The principal advantage of induction tempering is the possibility of integration with machine lines to avoid excessive handling of work, thereby minimizing labor cost. This is illustrated in the preparation of bar stock of specified mechanical properties before machining into cylinder head studs and miscellaneous machine parts. Another example of integration is the practice of using a 60-cycle ring-gear heater for simultaneous tempering and expanding of starter ring gears before shrinking them on the flywheel. The induction heating unit is simple, compact, and fits nicely in the machine line. It can be started or shut down, as needed, with other machines of the line; it represents a small initial investment and easily meets the production schedule.

Table VIII contains pertinent data from production installations that temper thousands of tons of bar stock each month by induction. The data are not intended to represent the limits of the process, but simply to give a set of conditions that have been found workable.

Selection of Equipment. Since tempering is performed below the lower transformation temperature (1333 F), lower-frequency induction tempering installations are generally used and are necessary for tempering large sections to minimize any temperature gradient from the surface to the interior. Table IX is presented as a guide for the selection of tempering equipment. It should be noted that line frequencies (60 cycles) may be used for tempering parts that have 1½ to 2-in. diam or larger. Considerable overlapping occurs in suitable frequencies so that equipment utilized for induction hardening can often be used for the tempering treatment as well.

Since the usual objective of induction tempering is to produce uniform hardness throughout the cross section, rather than to heat the surface, the power density is generally low (from 0.05 to 0.5 kw per sq in. of surface within the inductor). Actual power densities used in specific instances are given in column 6 of Table VIII. Furthermore, the heating time is comparatively long, to help provide uniform heating throughout the part. To meet production requirements, the length of the inductor or work coil is increased, or more than one bar is processed at a time.

The method described for determining the size of the unit to be used for through hardening by induction is also useful in induction tempering. Since induction tempering normally involves heating to a uniform temperature throughout the section, the required size of unit is most readily determined from a known value of the number of pounds that can be heated to the tempering temperature per kilowatt-hour and the production requirements in

Table VIII. Data for Progressive Induction Tempering of Medium-Carbon Steels (0.35 to 0.45% C)

Section Size, in.	Tempering Temp, deg Fahr	Heating Time,[a] sec	Frequency, cycles	Production,[b] lb per kw-hr	Inductor Input, kw per sq in.
1½	300	40	60	53.3	....
½ to 1 (irregular)	500	....	60	41	....
⅝ (flat)	550	68	60	63	0.06
⅞ (flat)	550	162	60	75	0.03
⅞ (flat)	700	162	60	41	0.07
½ to 1 (irregular)	1000	34.7	9600	18.7	0.40
½ (round)	1150	18.8	9600	13.8	0.35
⅞ (round)	1150	44.5	9600	12.8	0.28
1¼ (round)	1150	103	9600	13.2	0.19
1¾ (round)	1150	154	9600	11.8	0.18

(a) Total time (t) as determined from length of inductor (l) and rate of feed (r), $t = l/r$. (b) Power as measured at power line supply

Table IX. Selection of Power Source and Frequency for Various Applications of Induction Tempering[a]

Section Size, in.	Tempering Temperature, deg Fahr (max)	Frequency					
		Power Lines, 50 to 60 c	Motor Generators 1000 c	Motor Generators 3000 c	Motor Generators 10,000 c	Spark Gap 20 to 600 kc	Vacuum Tube over 200 kc
⅛ to ¼	1300					A	A
¼ to ½	1300				A	A	A
½ to 1	800 1300		A B	A A	A A	B B	B B
1 to 2	800 1300	B	A A	A A	B B	C C	C C
2 to 6	800 1300	A A	A A	B B			
Over 6	1300	A	A	B			

(a) Indicated selections are rated A as most suitable, B as suitable, C as satisfactory. Considerable overlap exists and specific frequencies can be used over a wide range of applications.

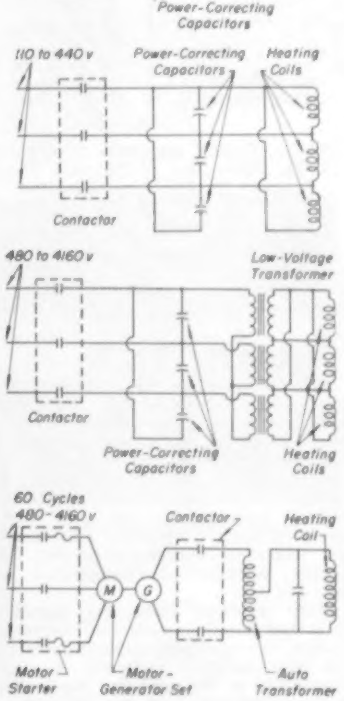

Fig. 23. Diagrams for 60-Cycle and Motor-Generator Installations for Induction Tempering

pounds per hour. Such data are included in column 5 of Table VIII.

Actual schematic diagrams of 60-cycle installations and motor-generator equipment now being used in induction tempering operations are shown in Fig. 23. The inductors or heating coils employed are primarily of the multi-turn type. For a given power density, the coils for lower-frequency installations require a greater number of turns. The application of higher voltages on the coil also requires a greater number of turns for a given power density. When using current directly from the power line at 440 v or more, the frequency is so low and the voltage so high that multiturn, multilayer coils are required for tempering operations. Such coils are expensive to build, and effective coupling is considerably more difficult. Accordingly, it may be advantageous to reduce the voltage to permit the use of a single-layer coil. The coils used with 1000, 3000 and 10,000-cycle equipment, as well as with higher frequencies, are of the single-layer type. Among motor-generator frequencies 10,000-cycle units require the fewest turns for equal applied voltages and power densities.

Auxiliary and Control Accessories. Since parts are cooled from the tempering temperature in air, no quenching facilities are required. However, equipment for handling is as important in induction tempering as in hardening; the fixtures already described for hardening are suitable. Frequently the tempering operation is keyed to the hardening operation, or the same equipment may be used for both induction hardening and tempering by simply changing the work coil or reducing the power density and the heating time.

In general, the control of induction tempering is achieved by selection of the power density and the rate of feed through the coil (scanning), based on hardness tests of the tempered product. Automatic control may be obtained at elevated tempering temperatures (above 800 F) by use of the special radiation pyrometer and high-speed controller previously mentioned. This arrangement may be used to vary the speed of the scanning operation continuously or to control the power.

With 60-cycle installations, an automatic voltage regulator in the power line ahead of the equipment is desirable if automatic control is not used. For adjustment, power input may be varied by one or more of the following means: (1) a continuously variable rheostat, (2) a continuously variable transformer, (3) a tapped transformer, (4) a saturable reactor and (5) taps on the coil itself. With motor-generator equipment employing automatic voltage regulation, or in scanning uniform work, control of the rectified field excitation has provided good results. Likewise, automatic voltage regulation is sufficient with vacuum tube equipment to give uniform results in small sections.

Selection of Induction Tempering Cycle. Fundamentally, the tempering cycle will be determined by the ultimate mechanical properties specified for the part. However, usual furnace tempering temperatures must be increased to compensate for the short heating times. Figure 24 shows the increase in tempering temperature required to produce a given hardness as the tempering time is decreased from 1 hr (furnace tempering) to 60 sec and 5 sec (induction tempering) in 1050 steel, quenched in brine from 1575 F. Pieces with small cross section may be air cooled immediately upon reaching the tempering temperature, while slower heating rates or short periods of time at temperature (5 to 60 sec) before cooling are desirable for larger sections, to allow penetration of heat. In scanning, of course, the power density, the rate of travel, and the length of the inductor will determine the time of tempering.

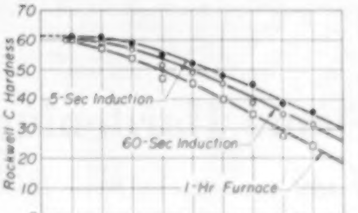

Fig. 24. Variation of Hardness with Tempering Temperature for Furnace and Induction Heating

Since it has been shown that the hardness obtained upon tempering is a function of the parameter $T(C + \log t)$, it is possible to determine the approximate temperature to be used for induction tempering if the time and temperature to provide the desired hardness in furnace tempering are known. For this purpose the following relation is useful:

$$T_i\,(C + \log t_i) = T_f\,(C + \log t_f)$$

where T_i and t_i are the induction heating temperature (deg Fahr + 460) and equivalent time respectively; and T_f and t_f are the known furnace tempering temperature (deg Fahr + 460) and time to produce a given hardness. The value of C is not critical and may be taken as 15 for constructional steels (0.25 to 0.50% C) and 11.5 for tool steels (0.90 to 1.2% C) when time is expressed in seconds. Strictly speaking, t_i and t_f are the time at temperature plus an equivalent time at temperature determined by heating to and cooling from the tempering temperature. In normal induction heating cycles the total induction heating time is suggested for use in preliminary estimates of the induction tempering temperature required. Final adjustments of the tempering temperature should be made experimentally.

Results of Induction Tempering. Proper selection of the induction tempering cycle and suitable equipment results in uniform hardness from surface to center of the part. This is well illustrated by Fig. 25, which shows hardness readings on the cross section of a 1¼-in. diam bar, made of TS14B35 steel, and through hardened and tempered. Statistical studies over the past several years on cross-sectional hardnesses for similar bar stock that was induction hardened and tempered by scanning reveal that 67% of all average cross-sectional hardnesses resulted in a hardness spread of ±1.25 Rockwell C points and that approximately 95% were within ±2.5 points. Variations in resultant hardness more often occur from differences in hardenability between respective heats of steel than from discrepancies in the induction tempering process. If each mill heat is run separately, it is possible to compensate for differences in hardenability.

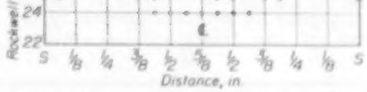

Fig. 25. Typical Hardness Survey on 1¼-In. Diam Bars of TS14B35 Steel Through Hardened and Tempered by Induction Heating

In spite of the short tempering times encountered in induction tempering, results indicate that the amount of stress relief is similar for parts uniformly tempered through the cross section if an equivalent hardness is obtained by higher tempering temperatures. After differential or selective tempering, the stress distribution may be substantially different from that achieved in furnace tempering, and careful analysis or a performance test should be conducted before adoption.

Cost Relations. Some indication of the operating cost for induction tempering by scanning may be obtained by reference to column 5 of Table VIII, and from a knowledge of the cost of electrical energy in a given plant location. Figure 26 shows the relative operating efficiency for electric tempering furnaces and induction tempering equipment. In the graph the area between the curves represents the range in pounds per kilowatt-hour for an electric tempering furnace. The plotted points, indicating pounds per kilowatt-hour for actual induction tempering installations, fall either within or above the range of operating efficiency for electric furnaces. When making a graphical comparison between the two types of heating, allowances should be made for the somewhat higher temperatures that are required when tempering by induction to attain the same hardness range and microstructure.

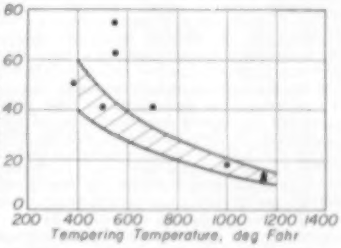

Fig. 26. Operating Efficiency for Tempering. Curves represent upper and lower efficiencies expected with electric resistance furnace. Actual operating efficiencies of continuous induction tempering installations are represented by plotted points.

Actual comparisons of cost should, of course, include the cost of initial equipment, labor costs and others, as pointed out in the article on "The Cost of Heat Treating" in the 1954 Supplement of the ASM Metals Handbook.

Flame Hardening

By the ASM Committee on Flame Hardening

Subdivisions

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FLAME HARDENING is a process of hardening a ferrous alloy by heating it above the transformation range by means of direct impingement of a high-temperature flame, and then cooling as required.

The flame hardening process utilizes air or oxygen and fuel gases and flame heads (for burning the mixtures) whose number, size and design are governed by the workpiece to be hardened. Depending on the fuels used, the flame head design, and the time of heating, the depth of the hardened zone can be controlled over a wide range from about 1/32 to ¼ in. or more. The process can be used for through hardening of workpieces 3 in. or less in diameter or cross section.

Scope and Application. Flame hardening is applied to a wide diversity of workpieces and ferrous materials for one or more of the following reasons. In all instances, of course, selective or localized hardening must be capable of satisfying the mechanical properties required of the part.

1 Where workpieces are so large as to make conventional furnace heating and quenching impracticable or uneconomical. Typical examples include extremely large gears, machine ways and rolls.
2 Where only a small segment, section or area of a part requires heat treatment or where heat treating all over would be detrimental to the function of the part. Typical examples include the ends of valve stems and push rods, and areas of wear on cams and levers.
3 Where dimensional accuracy of a part is impracticable or difficult to attain or control by furnace heating and quenching. A typical example is a large gear of complex design where flame hardening of the teeth would not disturb the dimensions of the gear.
4 Where the combination of steel and processing presents an over-all cost saving in comparison with other technically acceptable methods. A typical example is where a large carburized low-carbon alloy steel part might be made at less cost from a flame hardened plain carbon steel.

Methods of Flame Hardening

Four principal methods of flame hardening are in general use:

1 Spot or stationary
2 Progressive
3 Spinning
4 Combination progressive-spinning

Spot or Stationary Method (Fig. 1). In this method, selected areas of the work are heated locally by a flame head with either a single or multiple orifice (depending on extent of area to be hardened) and then quenched.

This method requires no elaborate equipment except perhaps fixtures and timing devices so as to make the operation uniform from piece to piece. Certain parts of light cross section requiring selective hardening away from extremities, and also parts on which the extremities are to be hardened are adaptable to being conveyed through the flame on a wheel or a chain, thus mechanizing the operation.

Parts heated by the spot or stationary method are usually quenched by immersion, though a spray of quenching medium directed onto the heated area may be feasible.

The Progressive Method (Fig. 2) is used to harden large areas that are beyond the scope of the spot or stationary method and other methods to be described. Progressive hardening employs a flame head, usually of the multiple-orifice type and with or without integrated quenching facilities that traverse the surface to be hardened. As the surface is heated progressively, the quenching medium is applied directly behind the flame head.

The equipment needed to flame harden by the progressive method consists of a flame head or heads mounted on a movable carriage running on a channel or track at a regulated speed. Flame cutting machines, for example, are adaptable to this type of flame hardening. Workpieces mounted on a turntable or in a lathe can be hardened readily by the progressive method. Either the flame head or the workpiece may move.

By having the flame head stationary, and making the workpieces progress under the flame head, provisions can be made to automate or mechanize the handling of workpieces.

Equipment for progressive flame hardening can be adapted to contour hardening on irregular surfaces by the use of the tracer-template method.

Supersedes the article on page 647 of the 1948 ASM Metals Handbook

There is no practical limit to the length of parts that can be hardened by this method, since it is a simple matter to make longer tracks over which the flame head will travel.

Where more than one pass is required to harden flat surfaces and where cylindrical surfaces are hardened progressively, such surfaces will exhibit soft spots because of overlapping or underlapping of the heated zone. Such effects can be minimized, however, by closely controlling the extent of this over-lapping.

The Spinning Method (Fig. 3) in its simplest form employs a mechanism such as a horizontal or vertical lathe to hold and spin the workpiece as it is being heated by the flame head or heads. When the piece has been heated properly, it is quenched by immersion or submerged spray.

This procedure is adaptable to extensive mechanization and automation, and commercially built machines are available that embody these characteristics. Such machines employ automatic timing, temperature and quenching control, usually leaving only loading and unloading operations to be done manually.

The spinning method is used for volume production of parts such as camshafts, small to medium-size gears, hubs, shafts and other parts.

The Combination Progressive-Spinning Method (Fig. 4), as the name implies, combines the progressive and the spinning methods for hardening long parts such as shafts and rolls. This method utilizes equipment similar to that described for the spinning method, except that the workpiece or the flame head or heads are moved to harden the piece progressively while it is spinning. The means of quenching are sometimes integrated into the flame heads, although a separate quenching ring may be used. It provides a means of hardening large surface areas with relatively low gas flows.

Progressive spinning units are generally designed to handle a broad range of diameters and lengths, and commercially built machines are available.

Fuel Gases

Since selection of equipment will depend on the gas used, the properties of fuel gases should be considered first. Table I lists the most commonly used gases, both naturally occurring and manufactured.

Table II shows the amount and cost of oxygen and fuel gas required to heat one square inch of steel to approximately 1500 F to a depth of ⅛ in., for various fuel gases burned with oxygen. The table also shows the normal oxy-fuel gas ratios used, approximate fuel gas costs and the relative heating times to attain the specified temperature and depth.

Table I. Fuel Gases Used for Flame Hardening

Gas	Heating Value, Btu per cu ft	Flame Temperature with Oxygen, deg Fahr	Flame Temperature with Air, deg Fahr	Usual Oxy-Fuel Gas Ratio	Usual Air-Fuel Gas Ratio	Form	Supply
Acetylene	1433	5620	4215	1.0	...	Gas	Generators and cylinders
City gas	300 to 900	4600	3605	(b)	(b)	Gas	Pipeline
Hydrogen	275	4975	3885	0.25	...	Gas	Cylinders
Natural gas (a)	1000	4900	3405	1.75	9.0	Gas	Pipeline
Propane	2520	4775	3495	4.0	25.0	Gas-liquid	Cylinders and bulk liquid
Air	...	...	...	...	...	Gas	Natural
Oxygen	...	...	...	...	...	Gas-liquid	Cylinders and bulk liquid

(a) Methane. (b) Varies with Btu content and composition

Bulk systems of supply for fuel gases greatly reduce their cost, but of greater importance is the elimination of cylinder handling and of the residual losses usually attending gases in cylinders. Bulk systems also provide a more constant supply of gas at uniform pressures.

Acetylene, when mixed with oxygen in a one-to-one ratio, gives a neutral flame of high temperature (about 5620 F). The ready availability of acetylene, oxygen and the equipment needed to burn the mixture, combined with the high flame temperature, makes acetylene the most widely used fuel gas for flame hardening.

Other fuel gases can be used for certain applications, provided equipment is designed for their use. The fuel gases can be mixed with oxygen or air to produce flame of varying temperatures.

Apart from the cost, availability and thermal properties of the gases, the details of the application itself will be a major factor influencing gas selection. For example, it is more difficult (longer time is required or greater flame-head capacity is needed) to heat the surface of a large mass to a given depth than it is to heat a small mass to the same depth. Therefore, on the surface of a large mass a high-temperature gas flame such as that produced by oxygen and acetylene would be preferred to an air-fuel gas or an oxy-nonacetylene fuel gas flame, to overcome the cooling effect of the heavy mass. On relatively small cross sections and on extremities having small cross sections to be flame hardened, lower flame temperatures can be used as developed by other fuel gases with air or oxygen.

Gas Consumption and Speeds. Gas consumption for flame hardening will vary with the thickness of the case to be obtained. Increasing or decreasing the depth of hardening will increase or decrease the amount of gas used. Massive parts increase gas consumption because of their greater cooling effect. In order to take advantage of the maximum flame temperature from the oxy-fuel gas flame, the distance from the end of the inner cone of the flame to the work should be 1/16 in.

The speed of travel of the flame head over the work, or the time of heating for the spot or spinning method, will vary with the thickness of case desired and the flame-head capacity. The proximity of the quench spray to the last row of flames will affect the speed somewhat in the progressive method. Progressive and progressive-spinning speeds usually vary between 2 and 12 in. per min for most applications, although very thin parts may be hardened at speeds as great as 100 in. per min or more to avoid overheating or burning. Because of the intense heat involved, the necessity for accurate control of the rate of travel in progressive and progressive-spinning methods cannot be overemphasized.

The time required for the spot or spinning method will vary with the depth of case and the flame-head capacity and can vary from a few seconds for a thin case on small pieces to 1½ min for a ⅛-in. case on a rail end. In the spinning method of flame hardening, the speed of rotation is relatively unimportant; depending on the flame-head capacity and the design of the part, it should be rapid enough to avoid overheating areas such as gear teeth and sharp corners. Surface speeds of 100 to 200 fpm are satisfactory.

Figure 5 shows the effect of linear speed on the surface hardness and the depth-hardness characteristics (penetration) of a 9½-in. diam bar of 1045 steel hardened by the combination progressive-spinning method.

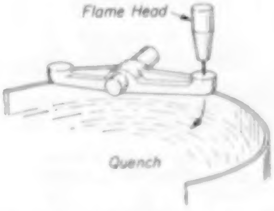

Fig. 1. Spot or Stationary Method of Flame Hardening

Fig. 2

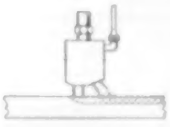

Fig. 3

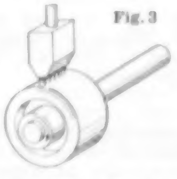

Fig. 2. Progressive Method of Flame Hardening

Fig. 3. Spinning Method of Flame Hardening

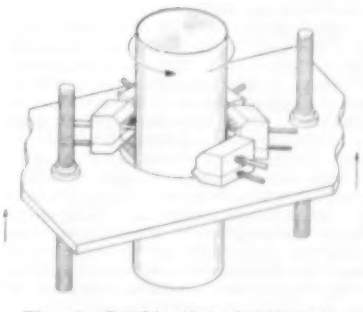

Fig. 4. Combination Progressive-Spinning Method of Flame Hardening

Equipment

Regardless of the flame hardening method selected, certain basic components of equipment are common to the process. The oxy-fuel gas flame head, for example, consists of a tube or a shell with an orifice or multiple orifices drilled into it; or the flame head may be fitted with removable orifices of the screw-in or inserted types through which the fuel gases issue and are burned (Fig. 6). A drilled-face flame

Table II. Cost of Oxy-Fuel Gas Required to Heat One Square Inch of Steel to 1500 Deg Fahr to a Depth of ⅛ In.(a)

Gas	Oxy-Fuel Gas Ratio	Basic Gas Cost, $ per cu ft(b)	Heating Time, sec(c)	Gas Consumption, cu ft per sq in.	Oxygen Consumption, cu ft per sq in.	Cost of Fuel Gas, $ per sq in.	Cost of Oxygen, $ per sq in.	Total Gas Cost, $ per sq in.
Oxygen	...	$0.006	...	...	...	...	...	...
Acetylene	1.1	0.016	10	0.25	0.275	$0.004	$0.00167	$0.00567
City gas	0.5(d)	0.0007	60	1.5	0.75	0.00105	0.00450	0.00555
Hydrogen(e)	0.25	0.010	30	0.75	0.187	0.0018	0.00113	0.00293
Natural gas(f)	1.75	0.0005	20	0.50	0.875	0.00025	0.0052	0.00545
Propane	4.0	0.0016	20	0.50	2.00	0.0008	0.0032	0.00400

(a) Data for all gases except hydrogen are based on actual test. Data for hydrogen are theoretical. (b) Subject to considerable variation depending on location and volume used. (c) Heating times are for general-purpose oxy-acetylene equipment. Specially designed gas equipment may be used to give heating time approaching that for oxy-acetylene. (d) Varies with Btu content and composition. (e) Hydrogen is seldom considered because equipment for its use is expensive and difficult to operate, and the gas is highly explosive. (f) Methane.

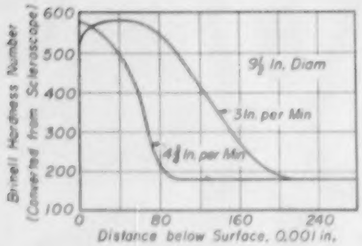

Fig. 5. Effect of Progressive Speed on Hardness Gradient in Flame Hardened 1045 Steel

head has a limited range of application, whereas a flame head with removable and replaceable orifices can be used over a wider range of applications by removing one or a number of the orifices and replacing them with plugs.

The heat output of the flame head is governed by the number and size of the orifices when all other factors are equal. The individual orifices range from No. 73 to No. 51 drill size (0.024 to 0.067-in. diam). Such small holes can readily become plugged, and when this occurs the flame head will not function properly. Flame heads with removable tips are usually more expensive initially but have the advantage that oversize or out-of-round holes, caused by mechanical or flame damage, can be corrected without replacing the entire head.

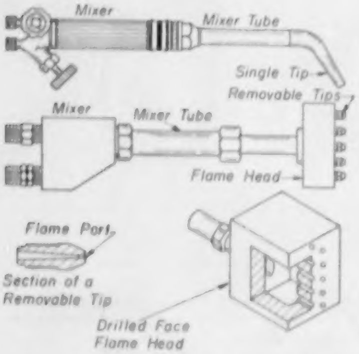

Fig. 6. Flame Heads for Oxy-Fuel Gas

Integral parts of the flame head are the mixer block and mixer tube, which mix the component fuel gases and convey them through the orifices (Fig. 6). The capacities of mixer block and mixer tube must match the number and size of the orifices; otherwise the flame will flash back and the flame head will not function efficiently.

Multiple-orifice flame heads are water-cooled because the high temperatures developed at and around the flame head would cause early deterioration. On flame heads used for progressive hardening, the quench water cools the head. On multiple-orifice flame heads used for spinning or progressive-spinning methods, the cooling water is circulated through chambers integrated into the head. Single-orifice flame heads—for example, a welder's torch—are generally not water-cooled.

Air-Fuel Gas Burners for flame hardening are always multiflame single heads, generally using heat-resistant refractory materials for the flame orifices. Such burners are generally designated as either radiant or high-velocity, direct-impingement type (Fig. 7). They consist of a refractory-lined, heat-resistant alloy casing with separate but integrated orifices through which the air-fuel gas mixture issues and is burned. The radiant type of burner is designed so that it radiates or reflects the heat of combustion to the work surfaces.

Most designs consist of a metal casing or shell with a plenum chamber at the input end. The gas-air mixture flows from the plenum through orifices or port plate and into the combustion chamber. This chamber is lined with a high-temperature insulating refractory material, as shown in Fig. 7(*b*).

The burner design is such that the burning gases heat the lining wall to a temperature near the theoretical flame temperature of the mixture. The reacting gases are preheated rapidly and the combustion process is greatly accelerated, as compared with more conventional gas burners.

The flame heads of both the oxy-fuel gas and the air-fuel gas methods of flame hardening are implemented by pressure regulators, valves, flowmeters and protection devices. In the air-fuel gas method, a separate mixer and compressor are needed, since the mixing function is not incorporated into the flame heads (Fig. 8).

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Materials of Construction for Flame Heads. Flame heads can be produced from many materials, but experience has shown that certain constructions offer definite advantages in life expectancy, cost and ease of fabrication. Life of flame heads will depend largely on the application, and it is difficult to predict exactly the life to be expected for a new application. Brass oxy-fuel gas flame heads used for progressive hardening of machine ways have shown an average life of 150 hr in continuous service 8 hr per day. For high-volume production, similar heads used on shafts, small gears and hubs have lasted more than 1000 hr. Materials of high thermal conductivity are recommended for oxy-fuel gas flame heads. Air-fuel gas flame heads of the high-velocity type, having Inconel casings and refractory liners used for spin hardening a gear, have a usable life of 10 to 15 weeks of continuous operation 40 hr per week. Water-cooled heads may last even longer before liners need replacement.

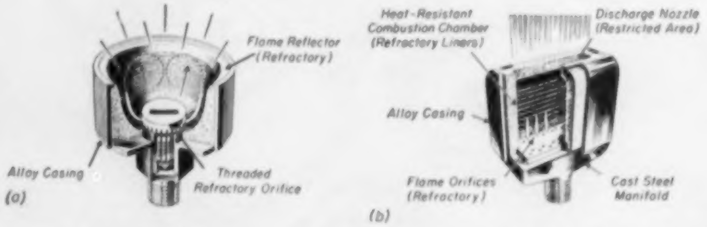
Table III shows materials of construction for flame heads.

Maintenance of Equipment

Flame Heads (Nonferrous) of the Oxygen-Fuel Gas Type. The main problems in maintenance of nonferrous flame heads are carbon deposits, erosion and corrosion. Experience with three types of flame-head construction (drilled port, inserted port and screw-in port) has shown maintenance problems common to all as follows:

Carbon Deposit. The intermittent igniting and extinguishing of the flame causes a small deposit of carbonaceous material to build up on the side walls of the port, from the retrogression of the burning fuel below the orifice of the port as the flame is extinguished. Although small for each cycle, the deposit will build up gradually until it causes a restriction in the port and thus a variation in the velocity of the gas. Several thousand cycles may be completed before it is necessary to clean the head.

A slight amount of cleaning can be done without removing the head from the mixer tube, by pushing a wire of the proper size through the port. However, excessive cleaning by this method results in a deposit of loose carbonaceous material in the fuel chamber, which may be moved by the velocity of the gas, causing it to become lodged in another port.



Flame Reflector (Refractory)
Alloy Casing
Threaded Refractory Orifice
(a)
Heat-Resistant Combustion Chamber (Refractory Liners)
Discharge Nozzle (Restricted Area)
Alloy Casing
Flame Orifices (Refractory)
Cast Steel Manifold
(b)

Fig. 7. Typical Burners for Air-Fuel Gas (a) Radiant Type (b) High-Velocity Type

Table III. Materials of Construction for Flame Heads

Material	Relative Machinability	Relative Thermal Conductivity	Melting Point, deg Fahr	Relative Hardness	Relative Cost	Remarks
60-40 brass	Very good	Very good	1660	Med hard	Low	Satisfactory service
70-30 brass	Very good	Very good	1750	Med hard	Low	Satisfactory service
Naval brass	Very good	Very good	1650	Med hard	Low	Widely used, highly acceptable
Copper	Good	Excellent	1981	Soft to med hard	Low	Very good because of excellent thermal conductivity, but difficult to drill small orifices
Inconel	Poor	Poor	2600	Med hard	High	Used extensively for heat-resistant casings to protect refractory inserts of air-gas burners
Monel	Poor	Poor	2370	Hard	High	Used for making orifice inserts into cast or wrought heads
Refractory	None	To suit	3000+	Hard	Low	Used extensively for air-gas burners; generally formed in steel dies and prefired in kilns. Requires protective jackets.
Stainless steel	Poor	Poor	2560	Hard	High	Sometimes used despite expense

Brasses other than the three mentioned may also be used. However, leaded brasses are unsatisfactory. Flame hardening heads have been made of steel, but flame erosion of the burner ports is rapid and slag may be picked up. Aluminum is not generally used because of difficulty in attaching connections and fasteners. In addition, it generally shows accelerated erosion from the flame, although a carburizing flame will minimize this effect.

Screw-in tips can be removed from the head and cleaned thoroughly by passing a wire through the port and pickling in a mild acid solution or cleaning in a solvent that will loosen the carbonaceous deposits. Solutions that attack the tip must be avoided lest the venturi or orifice be damaged. After the tips have been cleaned, they are replaced and operations can proceed. To save time, spare tips can be inserted when those in need of cleaning or repair are removed.

Drilled-port and inserted-port heads can be cleaned by passing a wire, or a drill one size smaller than the ports, through the ports and either pickling in a mild acid solution or cleaning in a suitable commercial cleaner. Again it must be remembered that any solutions used must not attack the head itself. After cleaning and rinsing in clean water, all traces of dirt and moisture must be blown from the flame ports and gas lines.

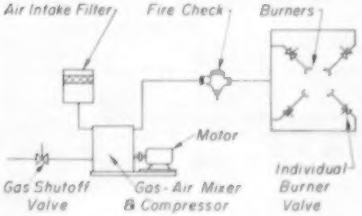


Fig. 8. Typical Mixer-Burner System for Air-Fuel Gas

Erosion and Corrosion. All types of heads are subjected to the by-products of combustion which may attack the face of the burner or the tips. Chromium flash on the burner face has proved helpful in reducing erosion and corrosion. In time the face of a drilled port burner may erode to a point where it is necessary to reface the head by machining and rework the counterbore. If there is enough space between ports on drilled-port heads, the port can be repaired by drilling oversize and pressing in an insert. These inserts can be removed when necessary and replaced.

The following procedures have proved satisfactory on volume production flame hardening operations: (1) pass a wire of the proper diameter through each flame port once during each shift of operation; (2) remove the flame head from the machine and clean thoroughly every 72 hr of operation for heads that have a 7 to 12-sec heating cycle, and every 120 hr of operation on heads that have a 13 to 25-sec heating cycle. The removal of the heads at the above intervals is not absolutely necessary, but it has been found practical, and gives work of high quality.

Because the oxy-fuel gas type of flame head is water-cooled, it may be necessary to soften the water to keep scale from forming in the cooling passages, in localities where extremely hard water is used. Commercial water softeners of the zeolite or polyphosphate type can be used to correct this difficulty.

Burners of the Air-Gas Type. Failures of air-gas burner liners occur by spalling and cracking of the refractory tunnel and outlet. Periodic examination is usually made at intervals determined by experience with the individual installation. Inspection may be required as often as once every shift where conditions are severe. The causes of deterioration are thermal shock from repeated and rapid heating or cooling or both, and mechanical shock from work striking the burners. The casings deteriorate mainly from prolonged exposure to escaping hot gases which heat the casings locally, causing more or less progressive oxidation, growth and, infrequently, burning. Where installation space permits, water or air cooling can usually be expected to increase the life of burners. Shielding, designed to conduct hot gases away from the burners and other parts of the machine, is also valuable in reducing maintenance costs.

Maintenance of Mechanical Components. Since both oxy-fuel gas and air-fuel gas systems employ pressure gages, pressure regulators, valves, flowmeters and protection devices, the maintenance problems of these accessories are common to both methods of flame hardening and are listed in Table IV.

Air-gas systems have maintenance problems relating to their compressors and blowers. Protection devices against backfire and explosion should be serviced according to the manufacturer's instructions.

Timers. When parts are being hardened on a timed cycle, periodic checks of the timers are advisable. Generally if the cycle is inaccurate it will be evident in the inspection of the parts.

Thermopiles. If the heating cycle is controlled by a thermopile several items must be checked. An excessive flow of cooling water through the housing will cause condensation on the lens. A deposit of any kind on the lens will cause erratic results. In high-production work the lenses are cleaned at least once each shift and preferably twice.

Holding Fixtures. It is important that the positioning of parts under the flame head be consistent. Therefore, holding fixtures should be checked and worn parts replaced before the parts become improperly located.

Piping. Types of piping and fittings recommended by underwriters should be used in installing the gas lines from the gas source to the site of use. In long gas lines means should be provided for purging accumulated condensate from the line before the gas reaches the mixing chamber or torch.

Precautions and Safe Practices

All fuel gases are explosive when mixed with either air or oxygen within their flammable limits. The affinity of oxygen for combustible materials increases as its purity increases. Both fuel gases and commercially pure oxy-

Table IV. Maintenance Problems in Flame Hardening Equipment

Component	Symptom of Trouble	Probable Causes
Pressure gages	Erratic behavior and erroneous results	Mechanical damage to mechanism
Gas-supply pressure regulators	Failure to hold pressure setting at outlet	Diaphragm broken or hardened Diaphragm too taut Sticking stem or valve parts Damaged or dirty valve seat or plug parts Broken or damaged spring
Solenoid valves	Failure to close or open	Defective valve mechanism or wiring
Fuel valve	Lazy flame lingering after shutoff	Dirty seat or stem Damaged seat
Oxygen valve	Short reports after shutoff	Damaged seat

gen must be transported, stored and used in compliance with established laws, rules and good practice. Anyone contemplating the installation of equipment for handling fuel gases and oxygen should obtain the necessary information. The manufacturers and suppliers of equipment and fuel gases generally are familiar with the requirements, and their apparatus will meet Underwriter's Laboratory standards for safe operation.

Information on cylinder storage, cylinder manifolding, acetylene generators, housing, and piping systems is obtainable in pamphlet form from the following organizations:

American Gas Association
Compressed Gas Association
International Acetylene Association
National Board of Fire Underwriters
National Fire Protective Association

Most state and local governments follow the recommendations of the above organizations in adopting regulations pertaining to gases. A study of local regulations should be made to determine whether there is any variance from standard procedures.

An operator should be taught to recognize faulty operation of valves and other equipment. He should recognize flashbacks and backfires immediately and shut off the gases. Regular testing with soapy water for leaking joints and connections in the whole system should be a part of the maintenance routine. Ordinarily no unburned fuel gas or oxygen should be allowed to escape to the atmosphere. However, this is sometimes necessary when setting gas flows and oxygen ratios or purging lines or torches. An air hose should be available to disperse the fuel gas quickly when it issues from the flame ports.

No lights or flames should be in the vicinity when fuel gas or oxygen is released into the air. Any spaces where the gases might accumulate in or around the machine should also be purged with the air hose.

Hand friction lighters should not be used to ignite the gases except for very small flame heads of low gas capacity. A flame from an acetylene torch or a burner using some other gas should be used. The pilot flame should be very close to the heating head so as to prevent an accumulation of gas and oxygen before ignition. For automatic flame hardening machines, the pilot light can be permanently mounted or electric-spark ignition can be used. When operations are stopped for any protracted length of time or for maintenance of the machine, the valves in the main supply lines should be closed. These valves must not leak, since even a small leak may cause a dangerous accumulation of gas.

Oil or grease may ignite violently in the presence of oxygen under pressure and must be kept away from cylinders, valves, bulk system fittings, couplings, regulators, hoses and other apparatus.

Cost of Flame Hardening

When a part can be heat treated by any of several methods, cost is the major factor in the selection. With large parts that would not be practicable to harden all over in a furnace, or with parts of complex design, selection is based more on necessity than on cost.

Short-run jobs can often be handled with simple equipment setups. Investment in special burners and quenching apparatus is economically justified for long runs, but an improvised arrangement of standard equipment should be used whenever possible.

When production quantities for a given part are large, automatic equipment of special design should be considered. Very often these machines can be loaded and unloaded automatically, thereby keeping labor requirements at a minimum. Even where the production of a single item is great enough to justify special automatic machinery, full consideration should be given to equipment with flexibility that permits handling other workpieces merely by changing fixtures and repositioning flame heads.

An initial investment in flame hardening equipment can vary between a

Table V. Cost of Flame Hardening a Small Gear
Part: Gear, ¾-in. face, 43 teeth, 8 DP
Hardened area: Teeth below root Production rate: 150 per hr

Item	Cost per hour for 2000-Hr Year		
Original investment	$30,000.00		
Fixed costs			
4½% interest on avg investment (½ original)	675.00	$0.337	
Amortization (6 yr of 2000 hr per yr)		2.500	
Maintenance of building, including heat, light, taxes, insurance and other maintenance for 200 sq ft at $0.29 per sq ft	58.00	0.029	
Total fixed costs			$ 2.866
Variable costs			
Fuel: C_2H_2, 156 cu ft per hr at $1.40 per 100 cu ft		2.184	
Water: 140 cu ft per hr at $0.16 per 100 cu ft		0.224	
Electricity: 1.5 kw-hr per hr at $0.01 per kw-hr		0.015	
Oxygen: 171 cu ft per hr at $0.55 per 100 cu ft		0.941	
Air: 760 cu ft per hr at $0.0048 per 100 cu ft		0.036	
General overhaul of equipment once a year:			
Labor, including burden	200.00		
Materials	20.00		
Other maintenance (burners)	500.00		
	720.00	0.360	
Total variable costs			$ 3.760
Labor			
Direct labor		2.100	
Indirect labor or burden		3.150	
Total labor cost			$ 5.250
Total cost per hour			$11.876
Total cost per piece ($11.876/150)			$ 0.079

Table VI. Cost of Flame Hardening a Starter Ring Gear
Hardened area: Teeth Production rate: 150 per hr

Item	Cost per Hour for 2000-Hr Year		
Original investment	$15,500.00		
Fixed costs			
4½% interest on avg investment (½ original)	349.00	$0.175	
Amortization (6 yr of 2000 hr per yr)		1.292	
Maintenance of building, including heat, light, taxes, insurance and other maintenance for 200 sq ft at $0.29 per sq ft	58.00	0.029	
Total fixed costs			$ 1.496
Variable costs			
Fuel: Natural gas, 210 cu ft per hr at $0.05 per 100 cu ft		0.105	
Water: 140 cu ft per hr at $0.16 per 100 cu ft		0.224	
Electricity: 1.5 kw-hr per hr at $0.01 per kw-hr		0.015	
Oxygen: 357 cu ft per hr at $0.55 per 100 cu ft		1.964	
Air: 760 cu ft per hr at $0.0048 per 100 cu ft		0.036	
General overhaul of equipment once a year:			
Labor, including burden	200.00		
Materials	20.00		
Other costs (burners)	250.00		
	470.00	0.235	
Total variable costs			$ 2.579
Labor			
Direct		2.100	
Indirect or burden		3.150	
Total labor costs			$ 5.250
Total cost per hour			$ 9.325
Total cost per piece ($9.325/150)			$ 0.062

Table VII. Cost of Flame Hardening a Cam

Part: Cam, ¼ in. thick by 4 in. wide by 12 in. long

Hardened area: Selected area of 15 sq in. Production rate: 175 per hr

Item		Cost per Hour for 2000-Hr Year	
Original investment	$12,500.00		
Fixed costs			
4½% interest on avg investment (2 shifts)	562.50	$0.141	
Amortization (6 yr of 2000 hr per yr)		1.042	
Total fixed costs			$ 1.183
Variable costs			
Fuel: Natural gas, 900 cu ft per hr at $0.06 per 100 cu ft		0.540	
Electricity: 4.1 kw-hr per hr at $0.009 per kw-hr		0.037	
General overhaul of equipment once a year:			
Labor, including burden	232.00		
Other maintenance (burners)	210.00		
	442.00	0.221	
Total variable costs			$ 0.798
Labor			
Direct labor (10 min each hour for loading machine)		0.350	
Indirect labor or burden		0.350	
Total labor cost			$ 0.700
Total cost per hour			$ 2.681
Total cost per piece ($2.681/175)			$ 0.015

Table VIII. Cost of Flame Hardening a Spur Gear

Part: Spur gear, 24-in. pitch by 1½-in. face

Hardened area: Teeth only Production rate: 10 per hr

Item		Cost per Hour for 2000-Hr Year	
Original investment	$20,000.00		
Fixed costs			
4½% interest on avg investment	900.00	$0.450	
Amortization (10 yr of 2000 hr per yr)		1.000	
Total fixed costs			$ 1.450
Variable costs			
Fuel: Mixed gas, 1750 cu ft per hr at $0.65 per 1000 cu ft		1.138	
Electricity: 11.9 kw-hr per hr at $0.009 per kw-hr		0.107	
Maintenance of equipment:			
Burners: Replace refractory inserts each 4 mo: 25 sets at $2.10; 8 hr of labor at $6.25 per hr (burden included) $102.50/667 (hr for 4 mo)		0.154	
Total variable costs			$ 1.399
Labor			
Direct labor		2.500	
Indirect labor or burden		3.750	
Total labor cost			$ 6.250
Total cost per hour			$ 9.099
Total cost per piece ($9.099/10)			$ 0.910

few hundred dollars for standard oxy-fuel heads and mixers to thousands for high-production machinery.

Cost analyses are given in Tables V to VIII for the flame hardening of four typical parts, as follows:

Example 1 (Table V). Gear having 43 teeth of 8 DP and ¾-in. face, hardened at the rate of 150 per hr by the spinning method with oxyacetylene

Example 2 (Table VI). Starter ring gear, hardened at the rate of 150 per hr by the spinning method with oxy-natural gas

Example 3 (Table VII). Cam, ¼ in. thick by 4 in. wide by 12 in. long, selectively hardened at the rate of 175 per hr in an area of 15 sq in. with air-natural gas through radiant burners

Example 4 (Table VIII). Spur gear having 24-in. pitch and 1½-in. face, hardened on the teeth only, at the rate of 10 per hr with air-mixed gas, through radiant burners

Quenching Equipment

In spot hardening, immersion quenching is generally used, but spray-quenching can be used for mechanized operations.

Parts heated by the progressive method are usually quenched by a spray integrated into the flame head, although for steels of high hardenability, or where it is desirable to vary or adjust the distance between the heated zone and the quench, a separate spray quench head is sometimes used. When integrated with the flame head, the spray quench should issue from the head at an angle away from the flame head to prevent interference with the heating, and must provide full coverage over the heated band. This type sprays the quenching medium on the work ⅝ to 1¼ in. behind the last row of flames when hardening 1045 steel.

Parts heated by the spinning method are quenched by several different procedures. In one, the heated part is removed from the area of heating and quenched by immersion in a separate quench tank. Another method integrates the quenching into the flame hardening machine; for example, after the part is heated by spinning, the arbor on which it is held is lowered into a quench bath to harden the part. Sometimes a spray quenching ring is submerged in the quench bath into which the heated part is lowered, to increase the rate of cooling over that of immersion quenching alone.

Parts heated by the spinning method may also be quenched with "quench blocks" on the same plane as the flame heads. When the heating cycle is completed and the flames are extinguished, the quench is turned on. The quench blocks should cover the heated band and provide enough quenching liquid to obtain suitable and uniform hardness. There should be enough quench points around the periphery of the block to envelop the area completely with quenchant.

Parts heated by the combination progressive-spinning method are usually quenched by a spray integrated in the flame heads or by separate quench blocks located below the flame heads.

For further information on quenching, the reader may refer to the article, "The Quenching Process and Industrial Quenching Equipment", page 620 in the 1948 ASM Metals Handbook.

Quenching Mediums

With spray quenching, either integrated in the flame head or by separate quench blocks, water or a dilute soluble oil solution is used as the quenching medium. Quenching oils should not be allowed to come in contact with oxygen or to contaminate equipment using it.

By reducing the pressure of the quenchant, the rate of cooling by spray quenching can be varied from the maximum for which the integrated or separate quench blocks are designed. Increasing the distance between the last row of flames and the point where the quenchant impinges will allow the mass of metal below the area to be hardened to extract heat and decrease the rate of quenching.

Compressed air, passed through the quench blocks, is used as a quenching medium in some applications. Still air can be used on air hardening steels.

Immersion quenches vary in type in relation to the metal used, the hardness level and depth desired, the mass and design of the part, and its dimensional tolerances. The quenching mediums can be caustic or brine solutions, water, soluble oil emulsions or any of a large variety of oils.

With any methods other than through hardening, the mass of cold metal underneath the heated layer aids the quenching by withdrawing heat.

Surface Conditions

In wrought steel parts the surface conditions likely to be detrimental to successful flame hardening are, in general, those that interfere with heating or quenching, cause localized overheating, initiate cracking, or cause a soft surface skin after proper heating and quenching.

Table IX summarizes the more common defects, their origin and the effects to be expected when they are present on flame hardened areas. The extent of these defects determines the amount of difficulty they may cause.

Operating Procedures

Speed of travel of the flame head, or the duration of heating, should be held constant for uniform results in flame hardening. In the progressive method, the flames gradually heat the workpiece in front of the flame head, and sometimes this effect must be compensated for by gradually increasing the speed of travel or by precooling. At the beginning of a pass when the progressive or progressive-spinning method is being used, the flame head or heads should be manipulated or otherwise adjusted to insure that the beginning of the area to be hardened attains the proper temperature and depth of heating as progression begins.

Pressures of the oxy-fuel gas or the air-fuel gas should be controlled closely for uniform input of heat. Flat oxy-fuel gas flame heads will be somewhat less efficient when used on circular or curved surfaces, because each cone of flame is a different distance from the work. Overheating leads to cracking.

Hardening temperatures can be judged by competent operators, but to the inexperienced the heated metal will appear colder than it actually is, because of the light from the burning gases; the consequent tendency is to overheat. Radiation or optical pyrometers are often used to judge more accurately the temperatures developed. Radiation-type pyrometer systems of fast response are used extensively to control work temperatures and heating times. Metallurgical examination is the best method for establishing operating conditions. Overheated spots may appear under individual flames, but with properly designed flame heads, this effect is minimized and not readily detectable by microscopic examination.

The success of many flame hardening applications depends largely on the skill of the operator. This is especially true where the volume of work is so small or so varied that cost of automatic control equipment is not justified.

The principal operating variables are:

1 Distance from inner cone of oxy-fuel flames to the work surface, or distance from air-gas burner to work
2 Gas pressures
3 Rate of travel of flame head or work
4 Type, volume and application of quenching medium

These variables must be closely controlled to insure duplication of desired surface hardness and depth of hardness. It is highly desirable to develop a specific procedure for each item to be flame hardened. The procedure is developed by preliminary tests on the production piece itself, if warranted, or on mock-up sections of approximately the same cross section as the production piece. After the desired contour and depth of hardened zone have been developed, the procedure is applied to production pieces and, when established, is made a part of the heat treating specification.

Table X gives a typical procedure for flame hardening a large ring gear and illustrates control of the process variables. Fig. 9 shows the gear.

Preheating

In flame hardening parts of large cross section, difficulty in obtaining the desired surface hardness and hardness penetration can often be overcome by preheating.

The hardness data in Fig. 10 show the effectiveness of preheating in developing hardness penetration in the same ring gear for which detailed procedures are itemized in Table X.

Flame hardening of prehardened and tempered steels, especially some of the alloy steels, requires careful control of heating to avoid cracking. Preheating of the part may be advisable to minimize the cracking of such steels.

Properties

In carbon steels, almost full hardness may exist in 50% or more of the total layer affected by heat. The transition zone gradually decreases in hardness until core hardness is reached. In a given steel, the more rapid the quench

Table IX. Surface Conditions of Wrought Steel Parts that Are Detrimental to Flame Hardening

Defect or Condition	Probable Origin of Condition	Detrimental Effects to Be Expected on Flame Hardened Areas
Laps, seams, folds, fins	Rolling mill or forging operations	1 Localized overheating or even surface melting with consequent grain growth, brittleness, and greater hazard of cracking 2 Where parts are to be used without final grinding these defects may cause excessive surface roughness.
Scale (adherent)	Rolling or forging, prior heat treatment, flame cutting	1 Insulating action against heating with resulting underheated areas and soft spots 2 Masking of quench causing soft spots 3 Potential machine difficulties[a]
Rust, dirt	Storage and handling of material or parts	1 Similar to scale as noted above 2 Severe rusting may result in pitted surfaces that will remain after hardening
Decarburization	Present in as-received steel bar stock; from heating for forging or prior heat treatment of parts or stock	In severely decarburized work, no hardening response will be found when parts are tested by file or other superficial means. Partial decarburization causes lowering of surface hardness as a direct function of the actual carbon content of the stock at the surface, provided the steel was adequately heated and quenched

(a) Scale and dirt that pop loose into the path of the flame often cause fouling of oxy-fuel burners. When these materials enter a closed quenching system, they may clog strainers and cause plugged quench orifices and excessive wear of pumps.

Table X. Typical Procedure for Flame Hardening a Large Ring Gear

(Figure 9 shows the gear.)

Preliminary and mounting on positioner	Gear should be centered on positioner to approx 0.065-in. total indicator runout on tooth OD.
Preheating flame-head gap	Set 3-in. max flame head at 7½-in. gap from flame hardened surface and approx 24 in. ahead of hardening tip.
Gas pressure (preheating)	13 psi acetylene, 27 psi oxygen
Flowmeter (for preheating gas)	2.1 divisions for acetylene, 2.65 divisions for oxygen
Tube readings (neutral flame)	Flutter approx ⅛ division + or −
Flame hardening heating head gap CAUTION: Must be kept parallel with flame hardened surface	Set and hold 5-in. flame head at ½-in. gap from flame hardened surface and at about 35 to 40-deg angle to radius; adjust during flame hardening to follow in line with roller path warp.
Gas pressure (flame hardening)	13 psi acetylene, 27 psi oxygen
Flowmeter (for flame-hardening gas)	2.7 divisions for acetylene, 3.2 divisions for oxygen
Tube readings (neutral flame)	Normal flutter approx 1.8 division + or −; watch frequently for signs of gas failure.
Water pressure (flame hardening quench)	Set pressure reducing valve for 30 psi.
Speed setting (Double check just before flame hardening)	(Preheating and flame hardening) No. 9 notch on positioner; equivalent to 6.42 in. per min on 228-in. circumference of 72½-in. flame hardened pitch circle; (approx 35.5 min per rev)
Preheat cutoff (to avoid softening of already flame hardened surface)	Kill preheat when spread of its flame toward oncoming hardened surface produces blue-purple temper color at flame hardening starting point. (Air-block flame head may be set up for the same purpose.)
Flame hardening heat cutoff (No overlap permissible; aim at ½-in. max soft gap. Use extreme caution.)	As flame hardening flame head approaches finish junction, back off tip 1/16 in. gradually during final ½ in. of gear travel and kill flame *abruptly* when nearest row of flames *just reaches* ¼-in. clearance from starting point of flame hardening, and immediately speed up table to fastest speed notch.
Hardness aim (except at flame hardening junction)	515 to 600 on portable Brinell at points 2 in. from ID of flame hardened roller path (Rockwell C 50 at approx 0.200-in. depth); total depth of contour, 5/16 in.

and the shallower the heated zone, the sharper is the hardness gradient. Thus, when air is used as the quenching medium, the transition zone is more gradual. The surface is likely to be slightly less hard when the hardened layer is thick. Thinner cases generally produce greater hardness at the surface. By adjusting the rate of heat input and rate of quench, the relationship between fully hard and transition zone material can be varied.

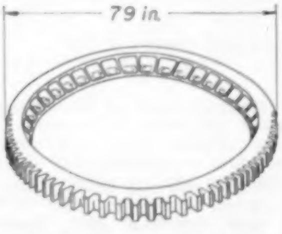


Fig. 9. Ring Gear for which Flame Hardening Procedure is Summarized in Table X. Gear is a 2500-lb. alloy steel casting with 4½-in. flame hardened face totaling 692 sq in. Gas cost, 0.46¢ per sq in.; total cost for gas, labor and overhead, 2.0¢ per sq in. or $13.84 per gear, using a flame head 5 in. wide at a travel rate of 6.42 in. per min. Hardening extended to a depth of 3/16 in. Brinell hardness at surface was 530 (see Fig. 10 below for hardness gradient.)

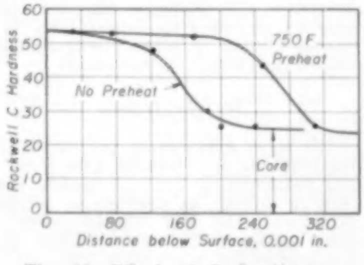


Fig. 10. Effect of Preheating on Hardness Gradient in the Same Ring Gear Dealt with in Table X and Fig. 9.

Tempering of Flame Hardened Parts

Flame hardened steel will respond to a tempering treatment as it would if hardened to the same degree by any other method. Standard procedures, mediums and temperatures can be used. However, for the class of work that is flame hardened because it is too large to be heated in a furnace, flame tempering may be the only feasible method of tempering available.

Large articles are usually hardened by the progressive method and can be tempered immediately by reheating the hardened surface with a flame head placed a short distance behind the quench. The reheating or tempering flame head must be designed correctly in regard to number and size of orifices or tips (flame ports) to produce the desired temperature and temperature gradient in the flame hardened zone at the flame hardening speed. Exact and final adjustments can be made by varying the flow of gases through the flame head and by adjusting the distance between flame head and work surface. Tempering flame heads must have smaller heat outputs than the hardening flame head, because too rapid heating of the hardened zone can cause cracking, and the temperatures required for tempering are lower.

Simultaneous hardening and tempering is of greatest value in treating the larger articles, but often it can be applied economically to smaller pieces.

On large parts flame hardened to depths of about ¼ in. or more the residual heat present after quenching may be sufficient to accomplish satisfactory relief of hardening stresses, and tempering by a subsequent operation may be unnecessary.

Where residual heat cannot be utilized and it is desirable to eliminate the tempering operation, the use of a lower-carbon steel is suggested if hardness requirements permit. Preheating of heavy parts will increase the residual heat available for tempering.

Selection of Material for Flame Hardening

Carbon Steels. The plain carbon steels are the most widely used for flame hardening applications. They can be hardened through in sections up to ⅜ or ½ in. This response permits the use of carbon steel for selectively flame hardened small gears, shafts and other parts of small cross section in which uniform properties are needed throughout the section. These same steels can be used for larger parts where hardness is necessary only to shallow depths of 1/32 to about ¼ in.

Carbon steels 1035 to 1053 are suitable for flame hardening; 1042 and 1045 are the most widely available and are recommended for all flame hardening applications except where they would be incapable of meeting requirements, as in the following examples.

1 The failure of a 1045 steel part to harden with a given quench would necessitate the use of a steel of higher hardenability—for example, one with higher carbon or manganese, or both, or possibly an alloy steel.
2 If increased depth of hardening is required, 1042 or 1045 may be inadequate when heavy sections are progressively hardened; so 1041, 1052 or an alloy steel would be necessary.
3 In applications where wear resistance is of prime importance, it would be advisable to use a steel of 0.60% C or more to produce maximum surfaces hardness. Steels of carbon content this high are often oil quenched to avoid the hazard of cracking in a water quench. Thus, greater hardenability may be needed with the higher carbon content.
4 In applications where a drastic quench in brine or caustic is required for hardening 1042 or 1045, and such quenching causes cracking, a steel of higher hardenability—either carbon or alloy—should be selected, which can be hardened by a less drastic quenching medium.

Alloy Steels. The use of alloy steels for flame hardening applications is justified only for the following reasons:

1 Where high core strength is required (before flame hardening) and where carbon steels are inadequate for the section sizes involved
2 Where mass and design are such that an alloy steel must be used to avoid the excessive distortion and cracking hazards that would be engendered by the use of a carbon steel quenched in water
3 Where suitable carbon steels are difficult to obtain.

Steels such as 4135-H, 4140-H, 8640-H, 8642-H and 4340-H are typical.

Carbon and alloy steel castings are widely used for flame hardening applications, and the selection of a specific composition or grade is made on much the same basis as for the wrought carbon and alloy steels.

For detailed information on the selection of steels, the reader may refer to the article "Selection of Constructional Steels" in the 1954 Supplement of the Metals Handbook.

Selection of Cast Iron. Gray cast irons and pearlitic malleable irons having combined carbon contents from about 0.25 to 0.85% are suitable for flame hardening. These cast irons respond to flame hardening the same as steel.

Cast irons having less than 0.25% combined carbon will not respond readily to flame hardening because of the inability of austenite to dissolve graphite during the extremely rapid heating of the flame hardening process. Malleable iron, in which all the carbon is in graphitic form, is not amenable to flame hardening for this reason.

Cast irons having combined carbon contents greater than 0.85% are difficult to flame harden because of their inherent brittleness and susceptibility to cracking when they are heated and quenched rapidly. The low melting point of cast iron and the presence of graphite in the microstructure make cast iron susceptible to "burning" or even local melting in flame hardening; therefore, extreme care is necessary when cast iron is hardened using equipment designed specifically for the flame hardening of steel. For example, the distance between the inner cone and workpiece can be increased or the flame velocity can be decreased. Smaller orifices in the flame head will also decrease the rate of heating.

Further information is given in the article "Selection of Gray Cast Iron", page 21 in this Supplement.

Other Materials. Flame hardening can be applied to other hardenable ferrous materials—for example, alloy cast irons, martensitic stainless steels and tool steels. Such materials may be flame hardened if special properties are needed, such as increased hardenability, resistance to corrosion and extreme resistance to wear. The nature of the flame hardening process, especially the relatively high temperature gradients produced and the higher than normal surface temperatures, may cause retention of excessive amounts of austenite in many of the highly alloyed materials, with possible low hardness and transformation to untempered martensite in service, with accompanying brittleness.

Carburized parts of plain carbon or alloy steels can be flame hardened to provide a hard case having high carbon content. The depth of carburized case may vary from a few thousandths to 1/16 in. or more. The flame hardening procedure is adjusted to heat the carburized case to its full depth for hardening. Since the core of low-carbon steels so treated does not harden substantially, the method provides a means of accurately controlling the depth of the hardened case.

Gas Carburizing

Part I — Commercial Practice

By the ASM Committee on Gas Carburizing

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GAS CARBURIZING is defined as a process in which the carbon content of the surface of a ferrous alloy is increased by heating the ferrous alloy in a gaseous atmosphere of such composition that the alloy absorbs carbon. A ferrous alloy is case hardened by carburizing and subsequently quenching from a suitable austenitizing temperature. The resulting combination of a hard, wear-resistant or fatigue-resistant surface supported by a tougher, ductile core is of great value in many engineering applications.

Sources of Carbon

The function of a carburizing medium is to supply an adequate quantity of carbon for absorption and diffusion into the steel. In current commercial practice, the two main sources of carbon are gases and easily vaporized hydrocarbon liquids.

Gases. The gases most commonly used are natural gas, "manufactured" gas and certain propanes (Table I). Butane is used infrequently and must be normal butane, not iso-butane. Where the demand for carbon is low, endothermic generator gas is a suitable source of carbon.

Natural gas and propane are the preferred sources when available with high purity. Propane with sulfur content up to 8 grains per 100 cu ft has been used without trouble. The best propane is derived from natural gas rather than from petroleum. Propane obtained as a by-product in oil refining frequently contains excessive amounts of ethylene, propylene and other unsaturated hydrocarbons that break down rapidly to oily soot or coke. Manufactured or city gas is frequently an undesirable source of carbon for carburizing. These gases are normally blends of coke oven gas, water gas and natural gas, which are maintained by law at a constant Btu heating value but have a variable chemical composition that may change frequently in a 24-hr period. This produces nonuniform carburizing, so this type of gas should not be used unless more effective gas is unavailable.

For uniform carburizing, circulation of the furnace gases is necessary. Since hydrocarbon gases provide large quantities of available carbon, relatively small flows of gas are required. The circulation resulting from gas flow alone is not always sufficient to produce uniform carburizing. In such installations it is essential that the furnace have a high-volume fan for forced circulation of the gases to all parts of the work load. Forced circulation also helps to prevent deposition of excess soot.

A more common commercial practice is to use an endothermic gas or a purified exothermic gas as a carrier and to enrich it with one of the hydrocarbon gases. The ratio of carrier gas to hydrocarbon gas varies widely in industry but is usually in the range of 8-to-1 to 30-to-1. The ratio used depends on the type of carrier and hydrocarbon gas, the furnace size and condition, amount of circulation and the work surface.

Although the use of carrier gases results in much better circulation because of the larger volume used, the additional forced circulation provided by a fan is desirable in promoting maximum uniformity of carburizing. This is particularly true of batch furnaces where the load density is great as compared with continuous furnaces where the loads are more open.

Liquids. Liquids also are used in rather large quantities as a source of carburizing gas. These liquids are usually proprietary compounds and range in composition from pure hydrocarbons such as terpenes, dipentine or benzene to oxygenated hydrocarbons such as alcohols, glycols or ketones. They may also be blends of hydrocarbons and oxygenated hydrocarbons. When a liquid is used it is normally pumped to a target plate in the furnace where it volatilizes rapidly, and the vapors then decompose thermally to provide the required carbon, with hydrogen, methane and carbon monoxide as secondary by-products.

Forced fan circulation is necessary in furnaces where a liquid is used for the carbon source, in order to have the flow direction such that the volatilized vapors "crack" on the work surfaces. This results in the formation of carbon on the steel surface where it can be absorbed immediately. The fan recirculates the "spent" gas, which acts as a carrier gas and dilutes the rich vapors to prevent excessive deposition of soot. Liquid sources can provide a chemically constant carburizing atmosphere, and are most suitable for use in remote locations where gas is not readily available. As raw materials the liquids are normally more costly than the carburizing gases. However, when the use of gas requires a carrier gas generator, the over-all cost for gas may be higher than for liquids because of the cost of operating and maintaining the generator.

Carrier Gases

The large majority of gas carburizing furnaces are operated with a carrier gas added to the hydrocarbon gas that is utilized as a principal source of carbon. The four common carrier gases are listed in Table II. Class 102 gas is listed but is not often used.

Class 102 gas by itself is decarburizing, so its successful use depends entirely on the addition of hydrocarbon gas. Under these conditions the ratio of carrier gas to hydrocarbon gas may be approximately 1 to 1, which results in excessive deposition of free carbon (soot or coke) on the work and in the furnace.

Class 202 gas offers a moderate range of control, some carbon availability for carburizing and continuous operation with dew points of –50 F or lower.

Endothermic gas (class 302) is generally the preferred type of carrier gas for use in gas carburizing furnaces and is the most widely used. It offers a wide range of carbon control, a moderate amount of carbon availability for carburizing, and continuous operation without weekend shutdowns for burnout when operating with dew points of +20 F and above.

Class 402 gas may be used as a carrier provided the equipment is designed to give the required control and a high cost for maintenance can be accepted.

Nitrogen gas is available from liquefaction plants, as a by-product from

Supersedes the article on page 688 of the 1948 ASM Metals Handbook

Table I. Principal Gases Used as Sources of Carbon in Gas Carburizing

Gas	Constituents of Gas, % by Volume CO_2	O_2	N_2	CO	H_2	CH_4	C_2H_6	C_2H_4	C_6H_6	Specific Gravity
Natural gas (Pittsburgh)	...	...	0.8	...	...	83.4	15.8	...	...	0.61
Natural gas (Kansas City)	0.8	...	8.4	...	...	84.1	6.7	...	...	0.63
Coke oven gas	2.2	0.8	8.1	6.3	46.5	32.1	...	3.5	0.5	0.44
Commercial (normal) butane	(C_4H_{10} is 93.0, and C_3H_8 is 7.0)									1.95
Propane	Commercial propane, 95% C_3H_8 with or without C_3H_6; natural gas propane, 95% C_3H_8									1.52

CH_4 is methane, C_2H_6 ethane, C_2H_4 ethylene, C_6H_6 benzene, C_3H_8 propane, C_3H_6 propylene, and C_4H_{10} butane.

oxygen plants or from modified exothermic generators (class 201). Nitrogen itself is neutral, but in commercial form it usually contains one or more minor impurities that may be oxidizing or decarburizing.

The inertness of pure nitrogen presents a problem of carbon control when this gas is used as a carrier for hydrocarbon gas. Because of the great capacity of the hydrocarbons to supply carbon to steel, the ratio of nitrogen carrier gas to hydrocarbon gas must be large—of the order of 50-to-1 to 100-to-1. Even more important, the hydrocarbon gas must be controlled within limits of about 0.1% to maintain carburizing potential within the close ranges of ±0.05% C. To date, the major use of nitrogen as a carrier gas has been confined to furnaces of large work-holding capacity and internal volume such as steel mill annealing covers. In such furnaces the atmosphere requirements are usually 1000 cu ft per hr, or more, and this flow is large enough to permit the use of controllable amounts of hydrocarbon gas.

Principal objections to the use of nitrogen as a carrier gas for carburizing include the following: Tank nitrogen or by-product nitrogen contains carbon dioxide, free oxygen and water vapor, which must be removed or rendered inactive to steel by the addition of hydrocarbons or hydrogen. Frequently the impurities vary in amount from time to time, thus making control difficult. Tank nitrogen in most locations is too expensive for use as a carrier gas. Generator nitrogen plus hydrocarbon gas may be noncombustible and may present a health hazard because of small amounts of carbon monoxide that remain unburned as it leaves the furnace. Also, generators for producing nitrogen gas are more expensive in initial cost and maintenance than the more suitable type of endothermic carrier gas generators.

Equipment for Carburizing

Gas carburizing may be carried out as either a batch or a continuous operation. In general, for large-volume production of similar parts with total case depth requirements less than 0.125 in. the continuous furnace is favored.

Batch Furnaces. There are three classes of batch furnaces: pit, horizontal and rotary retort. The pit-type units are suitable for all parts that require slow cooling and, with proper design of baskets or fixtures, parts can be quenched successfully. The horizontal units are more convenient for carburizing and direct quench applications where the work is moved to an enclosed vestibule and quenched. For batches of less than 2000 lb, the horizontal unit is an excellent furnace and, with an integral oil quench system, it can be placed in production lines. The rotary retort type is well suited for parts that are not damaged while tumbling at carburizing temperatures and that are to be direct quenched. Retort life in these units is usually good, often 12,000 to 15,000 hr of active life.

All furnaces should be as nearly gas-tight as possible in order to achieve good control. Before being placed in production, furnaces should be well "seasoned" by preheating and then carburizing for a minimum of 48 hr. Small batch-type units can be shut down over weekends or during slack production times and, with proper heating up and conditioning, can be placed in operation almost immediately.

Because circulation of atmosphere is very important in a batch furnace, where economy dictates that the density of load be high, a recirculating fan should be provided. Also, the furnace design should force the recirculated gases to follow a definite path through the load. Whenever possible, the work should be arranged to give turbulent gas flow without channeling, for maximum heat transfer and uniform distribution of atmosphere.

In pit furnaces, average life of heat-resistant alloy retorts or muffles and other heat-resistant alloy parts is about 5000 to 10,000 hr for good practice. The life of alloy parts is extended by not subjecting them to sudden changes in temperature. When not in production, pit-type units should be maintained at 1550 F with a minimum flow of carburizing gases. Pit furnaces require a minimum of maintenance but should be burned out or mechanically cleaned at weekly intervals. This prevents loss of efficiency and the occurrence of hot spots. Radiant tubes have a normal life expectancy of about 8,000 to 14,000 hr before repairs are required.

Table II. Principal Carrier Gases Used in Gas Carburizing(a)

Class	Method of Preparation	Ratio of Air to Gas(b)	Composition, % by Volume(b) N_2	CO(c)	CO_2	H_2(c)	CH_4	Dew Point, deg Fahr	Fuel Gas Required(d)	Cost, $ per 1000 cu ft(e)	Nature of Atmosphere
102	Exothermic base with rich mixture	6.0	71.5	10.5	5.0	12.5	0.5	(f)	155	0.085	Combustible; toxic; medium reducing
201	Prepared nitrogen base with lean mixture	9.0	97.1	1.7	...	1.2	...	−40	135	0.100	Noncombustible; inert
202	Prepared nitrogen base with rich mixture	6.0	75.3	11.0	...	13.2	0.5	−40	100	0.120	Combustible; toxic; medium reducing
302	Endothermic base completely reacted and cooled to eliminate breakdown of CO into C + CO_2	2.5	39.8	20.7	...	38.7	0.8	+25 to −5(g)	200(h)	0.230	Combustible; toxic; very reducing
402	Charcoal base	...	64.1	34.7	...	1.2	...	−20	12.5 lb charcoal	0.430	Combustible; toxic; extremely reducing

(a) Metal Progress Data Sheet 78, slightly revised. Compiled originally by C. C. Eeles and M. E. Shriner, from American Gas Assoc., Industrial and Commercial Gas Section, Information Letter No. 9. Complete Data Sheet is given as page 130-B of 1954 Supplement, Metals Handbook.

(b) Analyses based on 1000-Btu natural gas requiring 9.6 volumes of air for complete combustion. For other gases multiply the ratio of air to gas quoted by 0.5 for artificial gas high in hydrogen; by 0.4 for artificial gas with medium H_2, high CO; by 2.5 for propane; by 3.2 for butane.

(c) If made with artificial gas, the CO will be slightly lower and H_2 somewhat higher. With propane and butane the reverse will be true.

(d) "Fuel gas required" represents the cubic feet of 1000-Btu natural gas required to make 1000 cu ft of atmosphere. For other fuel gases multiply by 2.0 for high H_2 artificial gas; 2.5 for medium H_2, high CO artificial gas; 0.4 for propane; 0.3 for butane.

(e) Costs (in dollars per 1000 cu ft of atmosphere) are based on: natural gas at 40¢ per 1000 cu ft; electricity at 1¢ per kw-hr; water at 6¢ per 1000 gal; charcoal at 2½¢ per lb. Amortization is not included.

(f) Room temperature (cooling by tap water). May be reduced to +40 F by refrigeration unit, or to −50 by absorbents.

(g) Dew point is varied by changing the ratio of air to gas going to the generator. Most carburizing is done with dew point (at the generator) from +10 to +20 F.

(h) Plus 250 cu ft of fuel gas per 1000 cu ft of prepared atmosphere for heating retort.

Continuous Furnaces. Continuous gas carburizing can be accomplished in furnaces of the following types: chain belt conveyer, shaker or vibrator hearth, rotary hearth, rotary retort, and pusher. The construction of any continuous carburizing furnace must be such that air infiltration and contamination of the carburizing atmosphere by the quenching medium are kept at a minimum. In some types the furnace shell itself provides the necessary seal; with this construction all seams and joints must be welded gastight. In other continuous furnaces an alloy retort or muffle is used to provide an atmosphere seal. In furnaces that include direct quenching after carburizing, and in which the quenching medium also provides an atmosphere seal, it is often necessary to provide means of preventing the quenching vapors from contaminating the furnace atmosphere. This is particularly true when the quenchant is a water solution.

The chain belt conveyer, shaker hearth and rotary hearth furnaces are generally used for the lighter case depths of 0.020 to 0.025 in. or less. The rotary retort furnaces are frequently used for case depths of 0.075 in.

The pusher furnace is by far the most widely used type of continuous carburizing unit. Its construction usually consists of a gastight welded shell with gas-fired radiant tubes or electric elements for heating. The work is pushed through on trays with or without fixtures and, after completion of the carburizing cycle, may be quenched or cooled slowly as required. Circulating fans may or may not be used, but are often advisable for more uniform temperature and carburization. Most pusher-type furnaces are built with purging vestibules at the charge and discharge ends in order to reduce dilution of the furnace atmosphere by air. In many applications the continuous carburizer and quench are coupled with washing and tempering equipment to provide a fully mechanized heat treating line.

Maintenance

Following is a typical maintenance schedule for a pusher-type continuous furnace and auxiliary equipment:

Daily

1 Check temperature instrumentation.
2 Check level of oil for quenching.
3 Check flow of atmosphere gas and furnace pressure.
4 Check dew points and compositions of generator and furnace gases.
5 Check level of hydraulic oil.
6 Check flow of lubricating oil to fans.

Weekly

1 Clean washer.
2 Grease all fittings.
3 Clean air filters.
4 Clean orifice plates on atmosphere inlets and exhaust.
5 Inspect fixtures and trays.
6 Inspect safety devices.

Monthly

1 Burn out carbon deposits in the furnace. CAUTION: All the atmosphere gas must be removed first. The burnout must be done with restriction on the amount of air to be admitted to the furnace chamber to prevent the rapid oxidation of the carbon, thus preventing overheating of the furnace.

Every Six Months

1 Shut furnace down cold.
2 Vacuum clean furnace interior.
3 Inspect thoroughly and repair all alloy parts such as rails, fans, radiant tubes and work-handling fixtures.
4 Drain and clean quench tank.
5 Drain and clean parts washer.
6 Inspect and clean tempering unit.
7 Inspect and repair furnace brickwork.
8 Check all doors for possible leaks.
9 Inspect and clean all electrical contactors, solenoid valves, switches and motors.
10 Inspect and clean all heat exchangers.
11 Clean the exterior and repaint furnace.

ASM Committee on Gas Carburizing

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Metallurgical Engineer
Steel and Tube Div.
Timken Roller Bearing Co.

J. D. Armour
Chief Metallurgist
Union Drawn Steel Div.
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Chicago Screw Co.

E. P. Zink
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Allison Div.
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Safety

The gaseous carburizing mediums are highly toxic, highly flammable and form explosive mixtures rapidly. Piping and associated equipment should be carefully installed and maintained to prevent leaks. Operating personnel must be instructed carefully in the proper procedures for handling the various gases and liquids safely. Principal precautions are outlined in the Metal Progress Data Sheet published as page 112-B, Nov 1954. Additional data concerning the storage and handling of these materials are given in three pamphlets entitled "Fuel Gas", "Flammable Liquids", and "Liquid Petroleum Fuel Gases", published by Factory Mutual Engineering Div., Norwood, Mass. Insurance safety representatives can give helpful advice about storage and handling facilities.

Many carburizing units use propane gas either for heating or as an enriching gas in carburizing. Propane is heavier than air, and if leaks are present in the propane system, the gas will settle out in low places such as the pits under furnaces. Insurance companies have records of many fires and explosions caused by propane leakage. When propane is used in heat treating, a continuous alarm system may be employed. A device of this type continuously samples the atmosphere in furnace pits and other designated areas. If propane leaks occur, an alarm is sounded before the mixture reaches an explosive stage, and the gas can be diluted with air through the use of circulating fans or exhaust vents.

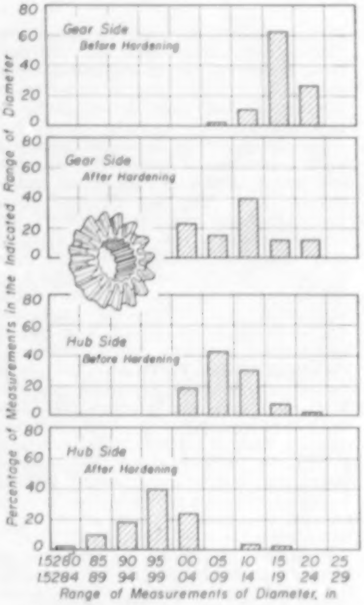

Fig. 1. Range of Measurements of Diameter Before and After Carburizing and Hardening 2½-Lb Differential Side Gears of Forged 8622-H Steel, Marquenched to 400 F

Preparation and Handling of Parts

Before carburizing, machined parts should be as near final dimensions as possible so that the outer, most effective case will not have to be ground off after carburizing, in order to meet dimensional requirements. Anticipated changes in dimensions during carburizing and hardening can be determined by careful measurement and machining limits established from such data. Methods of machining and quenching, case depth, size of section and grade of steel affect the amount of dimensional change. Figure 1 shows the ranges of dimensions before and after carburizing and hardening for a 2½-lb differential side gear forged from 8622-H and marquenched to 400 F.

While parts are being transferred from the machine shop to the carburizing furnace, they should be handled carefully to avoid nicks and surface damage that are costly to correct after hardening.

Cleaning. All parts should be thoroughly cleaned before they are charged into the furnace. These are some of the contaminants and their effects:

1 Sulfur-bearing oils or sulfur compounds react in furnace atmosphere to decrease the carburizing action and also the life of heat-resistant alloy parts and protective copper plating.
2 Lead oxide in lathe centers retards carburization and should be removed if carbon penetration is important at that point. Lead will interfere with the surface protection afforded by copper plating and will reduce the life of heat-resistant alloy parts. Organic paints should be used for marking, rather than the lead-base pigment type.
3 Iron oxides must be removed. Many gears are only partially machined, leaving the hubs and webs with the as-forged surface. If these were carburized without cleaning, the oxides would become flaky and spongy, falling off in assemblies, damaging bearings and contaminating lubricants.
4 Alkaline solutions are sometimes used for rust prevention on machined parts that are stored for a short time before carburizing and also to remove oil from the parts before carburizing. However, the residues from such solutions collect soot from the furnace and give a dark, dirty appearance to parts coming from the quench. Parts that require protection by alkaline powder during storage, should be rinsed thoroughly in uncontaminated hot water and allowed to dry before being charged into the carburizing furnace. Alkaline residues will also affect heat-resistant furnace alloys adversely.
5 Quenching salts may leave residues that are difficult to remove from trays, fixtures and work containers. If the same fixtures are later reused in furnaces, the atmosphere will be affected adversely.
6 Water in small amounts will upset the thermochemical balance of the furnace atmosphere. To avoid this, parts entering the furnace should therefore be thoroughly dry.
7 Trays should be degreased by burning off organic matter in a furnace.
8 Trichloroethylene residues from improper cleaning procedures can cause severe etching of the work.

Loading Methods. To obtain the maximum net load that can be carburized and quenched uniformly, the method of supporting the work in the furnace by trays, baskets, screens, spacers or other fixtures should be worked out carefully. Contact between the work and trays or baskets should be minimized. Contact between parts likewise is detrimental to uniformity of product. Overly dense loads result in the same damaging effects — uneven case and quench. The size and shape of parts will determine the method of loading for proper gas circulation and uniformity of hardening in the quench for parts that are quenched directly on fixtures.

Representative tray and fixture loading methods for use in continuous furnaces are illustrated in Fig. 2.

The bottom of the basket or tray must allow as much circulation as possible through it. Supporting fixtures, trays and baskets may be made from cast or wrought heat-resisting alloys. Welding should be done correctly, since any porosity or unevenness of surface may reduce the useful life of the alloy weldment.

The life of cast heat-resistant alloy in carburizing atmospheres is apparently governed more by the soundness of the casting than by any other factor. Rolled alloy is normally not subject to serious gas attack but may carburize. Rolled alloy is serviceable longer than cast alloy, provided the structure is not subject to failure in welds.

Quenching of Parts. When the load is removed from the furnace, it should be transferred to the quenching medium in the shortest time possible, because in an atmosphere-protected quench any delay will result in cooling of the surface. In removing parts into air for die quenching or for other reasons, the parts give up carbon rapidly, producing decarburized skin or scale.

Commercial Carburizing Practices for Undiluted Hydrocarbon Gases or Liquids

Undiluted hydrocarbon gases or liquids are normally used only in batch-type furnaces having effective door and cover seals and fans for recirculation. Because of the infiltration of air into continuous furnaces where the doors must be opened and closed for charging and discharging, a large volume of gas must be fed into the furnace. Since a large flow of hydrocarbon gas or liquid would cause excessive sooting, undiluted hydrocarbon gases or liquids are not employed in continuous furnaces; combinations of carrier gas and hydrocarbon gas are used.

In the normal operation of "seasoned" batch-type units, carburizing with undiluted hydrocarbon gases or liquids, the furnace is first brought to temperature with full gas or liquid flow above 1400 F and clean parts are then loaded into the hot furnace. The carburizing temperature is normally between 1650 and 1725 F. For most steels, 1700 F is used; for the more highly alloyed steels, such as 3310, 9315 and 4815, a temperature of 1650 F is more common.

For pit-type batch furnaces gas pressures from 0.3 to 6 in. of water are usually employed, depending on the type of seal. The carburizing fluids, whether natural gas, propane or oil, and the carburizing cycle, can be regulated for various desired surface carbon contents. The total case depth can be measured on specimens of steel similar to that being carburized (see article on page 686 of the 1948 Metals Handbook). The load is removed whenever the test specimens show the desired case. If the load must be transferred to a cooling pit, it is desirable to reduce the furnace temperature about 200 F below carburizing temperature, to minimize decarburization and oxidation during transfer.

The demand for carbon by the steel surface is greatest when the work first reaches carburizing temperature. To

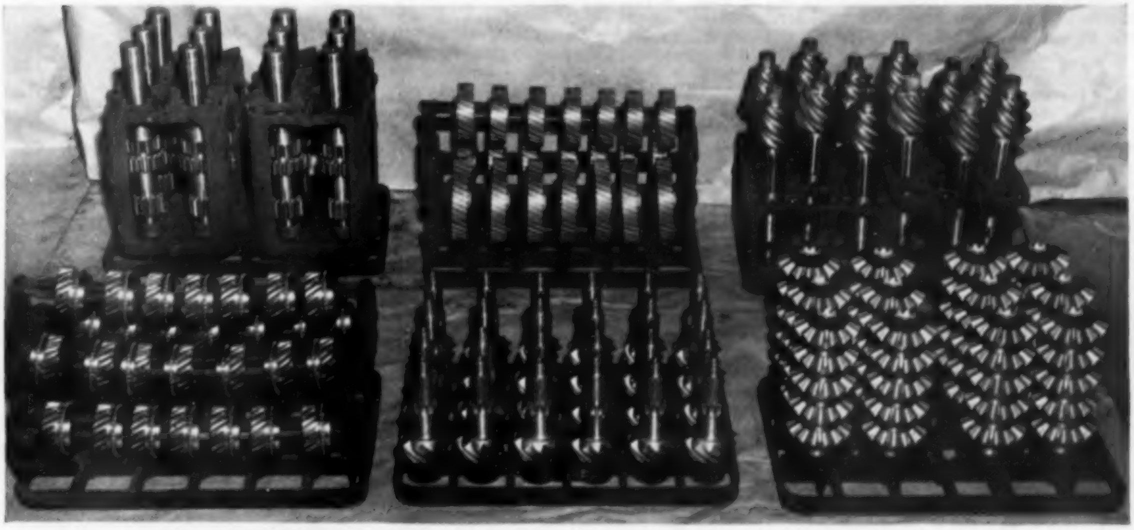

Fig. 2. Representative Methods of Loading Parts on Fixtures for Continuous Carburizing

minimize sooting, the hydrocarbon flow may be decreased progressively in accordance with the decreased demand. For a cycle in which the time at carburizing temperature is 9 hr, one third of the total carbon absorbed by the steel will be absorbed in the first hour, one third in the next 3 hr and one third in the last 5 hr.

Table III. Efficiency of Carbon Utilization in a Batch Furnace

Total Time, hr	Total Fluid, pints	Total Carbon in Fluid, lb	Total Carbon in Steel, lb	Total Carbon Absorbed, %
0.5	0.25	0.131	0.035	27
1.0	0.50	0.262	0.055	21
2.0	1.00	0.524	0.076	14.5
3.0	1.50	0.786	0.097	12.3
4.0	2.00	1.05	0.109	10.4
5.0	2.50	1.31	0.128	9.8
7.0	3.50	1.83	0.151	8.2

Load, 100 lb; surface area, 1440 sq in.

The efficiency of carbon utilization for a typical batch-type carburizing charge where the flow of carburizing medium was maintained constant for 7 hr is shown in Table III. These data indicate how the efficiency drops off to 10% or less, after about the third hour of carburizing and indicate the need for decreasing the flow of carburizing medium to obtain greater efficiency and less deposition of soot as the time cycle progresses.

Table IV gives typical carburizing procedures for a pit retort-type unit operated on liquid or propane gas for carburizing 2512, 2515, 3310, 9310 and 4815, to various total case depths with a desired surface carbon content of 1.00 to 1.05%. For operation on natural gas, flow rates would be in the range of 12 to 18 cu ft per hr for carburizing and 3 to 9 cu ft per hr for diffusion.

Costs

A summary of costs for gas carburizing in batch furnaces, comparing two types of work in two plants, is given in Table V. These costs were compiled for the following conditions:

Plant A. Batch-type furnaces, gas heated; 8500 tons of steel parts per year, the parts varying in weight from 1.5 to 7.5 lb each; production time, 8400 hr per year; case depth 0.060 to 0.095 in.

Plant B. Different type of part, different steel, different equipment; 10,000 tons of parts; uninterrupted production, 24 hr per day, 7 days per week, case depth between 0.050 and 0.090 in.

More complete information is available in the article entitled "The Cost of Heat Treating", on page 128, 1954 Supplement of the Metals Handbook.

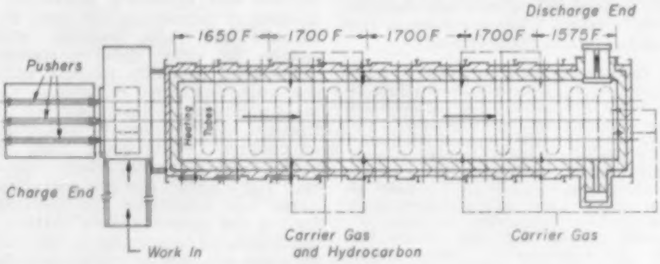

Fig. 3. Plan View of a Continuous Three-Row Carburizing Furnace Adapted for the Saturation-Diffusion Method

Commercial Carburizing Practices for Carrier Gas Plus Hydrocarbon Gas

The great majority of gas carburizing furnaces utilize combinations of carrier gas plus hydrocarbon gas. The use of undiluted hydrocarbon gas has been virtually eliminated in furnaces of the continuous type.

Introduction of Atmosphere. In batch furnaces, metered amountr of each gas are premixed and introduced into the carburizing chamber in sufficient quantities to insure correct operating conditions. This includes enough flow of atmosphere to maintain positive furnace pressure, to prevent infiltration of air and to carburize the work.

The location of the atmosphere gas inlet is important. The most logical and successful point for introduction is in the path of good gas circulation, for thorough mixing, but at a spot that will avoid direct impingement of the freshly added atmosphere on the work. This will usually avoid localized sooting and nonuniform carburization.

Flow Rates. Because of the small volume and tight chamber of batch-type furnaces, rather small volumes of gas are required. For a pit furnace having a work chamber of 25-in. diam and 36 to 48-in. depth, gas flows commonly used are 50 to 100 cu ft per hr of carrier gas and 8 to 15 of natural gas. If minimum sooting is desired, the flow of natural gas may be decreased as the cycle progresses, since the rate of carbon absorption at the surface of the steel decreases with elapsed time, as shown in Table III.

High rates of carrier gas flow with or without hydrocarbon gas may be required for purging batch furnaces to prevent oxidation of the newly charged work. This is particularly important when the work is copper plated to prevent carburizing of certain areas of the part. The protective copper can be destroyed rapidly by an oxidizing atmosphere at elevated temperature.

The high flow of hydrocarbon gas during the first part of the carburizing cycle is cut down or shut off during the diffusion and cooling cycles. This "program control", either manual or automatic, is designed to maintain control of carbon potential during all stages of batch carburizing.

In continuous gas carburizing furnaces good operating practice is not simply a matter of program control of gas ratios over a timed period. Rather it becomes a more complex arrangement of zoned control of gas ratios along the length of the furnace. To combine a carbon saturation and a diffusion cycle in a continuous furnace, required amounts of atmosphere gas must be provided from multiple inlets staggered along both sides of the furnace for better distribution of atmosphere. The mixture of carrier and active gas introduced through the ports of the various zones may be the same or may be varied purposely. Figure 3 illustrates a continuous three-row carburizing furnace adapted for the saturation-diffusion method of carburizing. Multiple manifolding for atmosphere distribution is shown. Main-

Table IV. Typical Carburizing Procedures for a Pit Retort-Type Furnace Using Undiluted Fluids

Case Depth to Core Carbon, in.	Carburizing: Time, hr	Carburizing: Liquid, pints/hr	Carburizing: or Propane cu ft/hr	Diffusion: Time, hr	Diffusion: Liquid, pints/hr	Diffusion: or Propane cu ft/hr	Total Time, hr
0.015 to 0.020	1¼	¾	5	0	..	..	1¼
0.020 to 0.025	1¼	¾	5	½	½	2	1¾
0.025 to 0.030	1¼	¾	5	1	½	2	2¼
0.030 to 0.035	1½	¾	5	1¼	½	2	2¾
0.035 to 0.040	2	¾	5	1½	½	2	3½
0.040 to 0.045	2½	¾	5	2	½	2	4½
0.045 to 0.050	3	¾	5	2½	½	2	5½
0.050 to 0.055	4½	¾	5	3½	½	2	8
0.060 to 0.070	8	¾	5	5	½	2	13

Work container, 25-in. diam by 36 in. deep. Load of gross weight 900 lb, net weight 300 lb, consisted of aircraft gear parts, packed and spaced in the container. Carburizing temperature, 1650 F. Time shown is time at temperature as indicated by recorders. Desired surface carbon content (aim) was 1.00 to 1.05%.

Table V. Costs of Gas Carburizing in Batch Furnaces in Two Plants

Item	Cost per ton: Plant A	Cost per ton: Plant B
Direct labor	$ 3.93	$22.00
Indirect labor	1.27	7.92
Expendable supplies ...	8.05	17.14
Maintenance		
Labor	0.69	3.65
Materials	2.64	21.52
Cost per ton............	$16.58	$72.23
Cost per pound	0.0083	0.0361

Detailed analysis of costs for Plant A are given in Tables VII to XII of the article on page 128 of the 1954 Supplement to the Metals Handbook. The total costs are 31% higher than the total of the five items that are shown here.

tenance of different carbon potentials in the different zones, as required by the saturation-diffusion treatment, will require suitable built-in baffle arches at certain locations within the furnace. Also, correct directional flow of effluent gases from the ends of the furnace must be established and maintained.

In the operation of a multiple-row gas carburizing furnace, it is sometimes desirable to operate each row at a different pushing speed in order to produce two or more different carburized case depths simultaneously. The weight in pounds per hour of the steel loaded on the different rows must be approximately balanced to insure all rows coming to temperature at about the same point in the furnace. Thus slower moving rows are not subjected to "shadowing" from the faster moving rows. By establishing a uniform zone for heating all work regardless of differences in rate of movement through the furnace, the atmosphere can be controlled in the succeeding zones so that all work, even though of different case depth from row to row, will have the same controlled carbon treatment.

It is advisable to set some practical limits on the different case depths to be obtained from row to row. The most commonly accepted limits are about 0.015 to 0.020-in. differential for trouble-free operation.

For large continuous furnaces, the required flow of carrier gas to the carburizing chamber in order to produce adequate furnace pressure is from 1 to 3 volume changes per hour.

Natural gas as the active addition agent will range from 3 to 15% of the carrier gas. For propane, 1 to 5% will give equivalent carbon in the atmosphere. The rate of flow of each gas is continually measured and indicated either by visual flow meters or by a manometer connected across an orifice of known diameter.

Dense loads of large surface area will require somewhat higher ratios of hydrocarbon to carrier gas to insure uniform carbon concentrations and case depths throughout the load. This factor is more critical in applications where the degree of recirculation is low or nil.

Furnace pressures of 0.2 to 0.3 in. of water are common and can be measured most accurately by means of a draft gage. The presence of burning gases at the effluent ports at the top of the furnace is not an indication of positive pressure in the furnace. The hot gases are lighter than air and will rise. While they are burning out of the effluent port, air may be drawn into the furnace through leaks in the bottom casing or around fan shafts. This emphasizes the need for tightly built and maintained furnaces for continuous gas carburizing under conditions requiring carbon control.

The time interval between door openings on continuous furnaces may range from less than 5 min to 40 min or more, depending on the length of the furnace and the case depth required. Parts such as automotive ring gears that are quenched individually in presses directly from the carburizer may require the opening of an auxiliary slot type of door every 30 sec. In general, greater total gas flows and richer mixtures are required for applications where door openings are frequent. Vestibules may be swept out with natural gas immediately after the outer doors are opened and closed.

Mixing. Almost always, the carrier gas is mixed with hydrocarbon gas outside continuous furnaces. This may be done with individual mixers at each inlet or by one or more central mixing stations from which the mixtures are manifolded to several furnace inlets. With central mixing stations a constant ratio of carrier gas plus hydrocarbon gas can be maintained at any or all sections of the furnace regardless of intentional flow changes or accidental changes in line pressures of either carrier gas or hydrocarbon gas.

A constant-ratio mixing station may be an arrangement of correctly sized orifice plates in the carrier gas and hydrocarbon gas supply lines augmented, in the hydrocarbon gas line, with a pressure regulator that is back-loaded from the carrier gas supply line. In this manner the supply pressure of hydrocarbon gas is made dependent on the supply pressure of the carrier gas, and the respective gas flows across both orifices are maintained at constant ratio over a wide range of gas flows.

Sooting

An excessive amount of free carbon (soot or coke) deposited on the work and in the furnace causes loss of control of the carbon potential, uneven carburizing, deterioration of furnace alloy and refractory, high cleaning costs and unpleasant working conditions.

Sooting has always been a problem in gas carburizing. It can be minimized by the choice of atmosphere; for example, the more common use of carrier gas plus hydrocarbon gas, rather than straight hydrocarbon fluid. The problem can also be minimized by a judicious choice of flow rate so as to give a rapid rate of carburizing without excessive sooting. Another effective method includes the use of a diffusion cycle, which in many instances permits the soot to be removed from the work by reaction with the carrier gas or with regulated amounts of air introduced for that purpose.

In muffle, pit or batch furnaces, soot presents a greater problem because a relatively smaller volume of gas is usually changed from three to five times per hour in order to insure availability of carbon. In large, continuous, radiant-tube furnaces where the ratio of gas volume to the area to be carburized is much greater, the atmosphere is changed from one to three times per hour.

Parts are frequently processed in pit furnaces and transferred to cooling pits when finish machining is required before hardening. Under such conditions it is sometimes advantageous to have a small amount of soot on the parts to protect them against decarburization and oxidation during transfer.

Soot deposition in endothermic generators can be minimized by operating at air-gas ratios set to produce carrier gas of dew point greater than +10 F, and by operating the generators at a uniform flow, allowing the surplus gas to be exhausted instead of attempting to regulate the flow to the demand, if the demand varies over a wide range.

Most continuous carburizing furnaces are "burned out" periodically to remove soot when the furnace is empty during a weekend. This is accomplished by partially opening the doors to allow air to flow through, or by introducing controlled quantities of air from the combustion blower through a series of ports along both sides of the furnace and under the furnace hearth. When starting up a furnace after such a "burnout", the hydrocarbon additions may have to be increased for the first 8 to 16 hr of operation to give the desired carbon potential. More hydrocarbon may also be required when new trays or other new alloy parts are first put into the furnace. When such a situation exists, the furnace is said to be "underconditioned".

Low Surface Carbon

Most steels can be carburized by the carbon saturation - carbon diffusion type of cycle to produce surface carbon content well below saturation; for example, from 0.90 to 1.00% C.

There is a strong trend in present carburizing practice toward surface carbon concentrations of eutectoid composition or slightly higher. With the leaner alloy steels now being used, it becomes increasingly important to utilize the full hardenability of the steel. Maximum hardenability of the alloy carburizing steels most commonly used is obtained at carbon concentrations near eutectoid composition. The excess carbides commonly found with high carbon concentrations promote the formation of transformation products other than martensite, and may also remove part of the carbide-forming elements from the austenite, thus decreasing the effective hardenability.

Low carbon concentrations at the surface also permit the economy of direct quenching of work from the carburizing furnace, instead of reheating. Direct quenching of carburized parts having high surface carbon concentrations favors the retention of austenite. Such austenite is undesirable because it lowers the indentation hardness of the case and promotes secondary hardening with the formation of untempered martensite, which may change the dimensions of the finished parts as well as embrittle them.

Where surface carbon concentrations near eutectoid composition are desired, a multiple-manifold arrangement may be used by which part of the carrier gas and all of the hydrocarbon gas are introduced through ports in the front portion of the carburizing zone where the carbon demand is high. The gas supplied to the other zones is carrier gas only, with the carbon potential adjusted to give the desired final surface carbon concentration.

Since, for a given carbon content of the core, the diffusion rate of carbon in austenite decreases with a lowering of surface carbon concentration, this "starved carbon" method requires a longer cycle. Also, good recirculation of gases is essential. The atmosphere adjacent to the work becomes quickly depleted of available carbon, and if stagnant areas are allowed to exist, excessively low surface carbon concentrations and shallow case depths on the work in these areas will result. Many continuous carburizers recently installed for this type of carburizing have recirculating fans, and similar fans are being installed in some of the older existing furnaces.

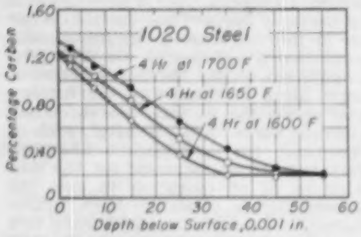

Fig. 4. Carbon Gradients in 1020 Steel, Carburized 4 Hr at 1600, 1650 and 1700 F

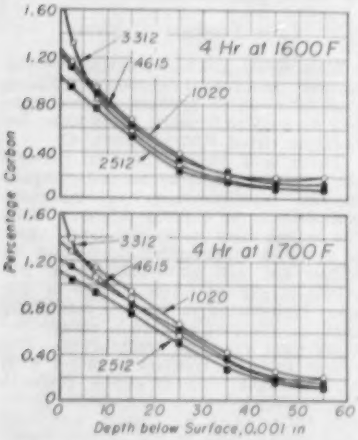

Fig. 5. Carbon Gradients in Four Steels After 4 Hr at 1600 and 1700 F

Control of Case Depth and Carbon Concentration Gradient

The carbon concentration gradient of carburized parts is influenced by the carburizing temperature and time, type of cycle (various combinations of carburizing and diffusion times), the carbon potential of the furnace atmosphere and the original steel composition.

Figure 4 illustrates the influence of carburizing temperature on the carbon gradient for normal carburizing (that is, with saturated austenite at the surface) for a 1020 steel carburized in a typical batch-type unit.

Carbon gradient curves obtained in a typical batch-type unit giving saturated austenite at the surface are shown for four carburizing steels in Fig. 5. Figure 6 illustrates two types of gas carburized cases obtained in the same continuous furnace operating under identical time-temperature cycles but with different conditions of atmosphere control.

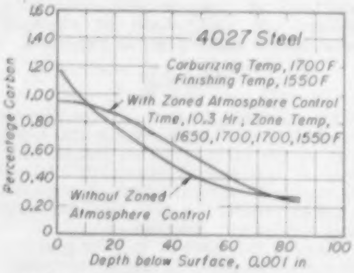

Fig. 6. Carbon Gradients from Continuous Carburizing Furnaces

The case with the higher carbon content at the surface in Fig. 6 was produced without consideration of high demand for carbon early in the carburizing cycle and low carbon demand during the final part of the cycle. A uniformly distributed mixture of carrier gas plus hydrocarbon gas was admitted at various points along the length of the furnace. The ratio of carrier gas to hydrocarbon gas was high enough to insure minimum soot deposition during the carburizing and cooling portions of the cycle.

The other curve in Fig. 6 was produced under identical conditions, except for the distribution of atmosphere within the furnace; the total amount of hydrocarbon gas required was admitted at several points in the carburizing zones, with the greatest amount added in the first of these zones. Carrier gas without enrichment was added in the diffusion and cooling zones.

The typical influences of carburizing time and carbon potential of the furnace atmosphere on the carbon gradient in a 1022 steel (plotted as average carbon at the cut midpoint) are shown in Fig. 7 and 8.

Temperature

The maximum rate at which carbon can be added to steel is limited by the rate of diffusion of carbon in austenite. The diffusion rate increases greatly with temperature and the rate of carbon addition at 1700 F is about 40% greater than at 1600 F.

The temperature most common for carburizing is 1700 F. This temperature gives a satisfactory compromise between a rapid carburizing rate and reasonable maintenance of furnace equipment, particularly heat-resisting alloys. For shallow case carburizing where the case depth must be within a narrow specified range, lower temperatures are frequently used, since case depth can be more accurately controlled with slower rates of carburizing.

For consistent results in carburizing, it is important that the temperature be uniform. Uniformity in various locations throughout the work load depends on furnace design, load density, recirculation and heating rate. With high density of load, batch furnaces should be provided with a recirculating fan (see "Batch Furnaces", page 133).

For a given density of load the difference in temperature between the outer and inner portions of the load may be high at carburizing tempera-

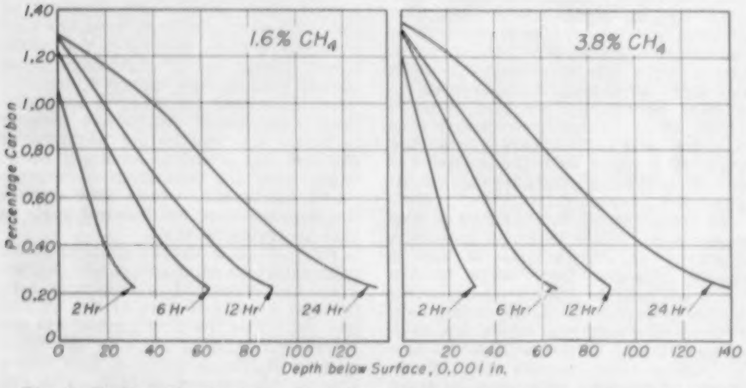

Fig. 7. Carbon Gradients in Test Bars of 1022 Steel Carburized at 1685 F in 20:40 CO:H_2 Gas with 1.6 and 3.8% CH_4 Added (H. M. Heyn)

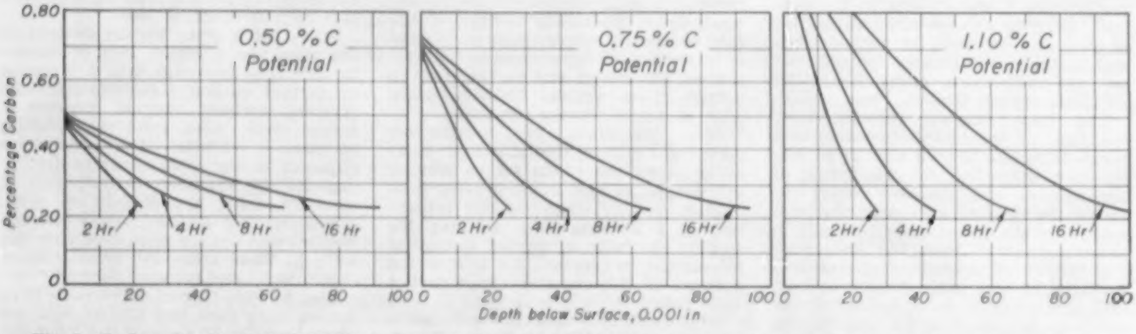

Fig. 8. Carbon Gradients in 1022 Steel, Carburized with 20:40 CO:H_2 Gas Containing Enough H_2O to Produce Carbon Potentials of 0.50, 0.75 and 1.10% C; Temperature 1685 F (H. M. Heyn)

tures, because the outside of the load is heated primarily by radiation and the rate of heating is rapid at carburizing temperatures. Also, the ability of the recirculated gas to decrease such differences in temperature is limited because of the low density of the gas at these temperatures.

At lower carburizing temperatures (1550 to 1600 F) a given difference in the time required for different parts of the load to reach temperature has a smaller effect on the case depth.

Other factors that cause high temperature differences are high ratio of surface area to volume of the individual parts, and high heat input. Nothing can be done about the ratio of surface to volume, but heat input can be regulated automatically with what is known as a heat input controller, to minimize temperature differentials throughout the load.

For best control in batch furnaces the thermocouple should be placed so that it reaches control temperature before any part of the charge. In continuous furnaces, the thermocouple should be as close as possible to the work without danger of interfering with the flow of work through the furnace. For facility in checking, the thermocouple and protection tube are usually located through the sidewall of the continuous furnace. Since the first zone of a continuous furnace is a heating zone, the temperature-control thermocouple of this zone should be placed near the last part of the zone to insure against overheating the work. The thermocouple in the carburizing zones should be approximately in the middle of the zone. When the temperature of the last zone is lower than the carburizing temperature, for quenching purposes, best control is obtained by having the control couple near the discharge end of the zone.

If the chromel-alumel thermocouples commonly used at carburizing temperature are allowed to come in contact with reducing gases like those in the carburizing chamber, accuracy of the couple is rapidly destroyed. Protection tubes are required.

Virtually all carburizing furnaces now in use have satisfactory automatic control of temperature. However, errors in measurement of temperature do occur occasionally. Because of the value of the machined parts contained in large furnaces, in addition to the value of the equipment itself, frequent temperature checks are advisable.

Effect of Time

F. E. Harris has developed a formula for the effect of time and temperature on case depth for normal carburizing (Metal Progress, Aug. 1943):

$$\text{Case Depth} = \frac{31.6\sqrt{t}}{10^{\left(\frac{6700}{T}\right)}}$$

where case depth is in inches; t is time at temperature, in hours; and T is the absolute temperature (deg Rankine = deg Fahr + 460).

For a specific carburizing temperature the relationship becomes simply:

$$\begin{aligned}\text{Case Depth} &= K\sqrt{t}\\ &= 0.025\sqrt{t} \quad \text{for 1700 F}\\ &= 0.021\sqrt{t} \quad \text{for 1650 F}\\ &= 0.018\sqrt{t} \quad \text{for 1600 F}\end{aligned}$$

Table VI. Values of Case Depth Calculated by the Harris Equation

Time, t, hr	Case Depth after Carburizing at 1600 F	1650 F	1700 F
2	0.025	0.030	0.035
4	0.035	0.042	0.050
8	0.050	0.060	0.071
12	0.061	0.073	0.087
16	0.071	0.084	0.100
20	0.079	0.094	0.112
24	0.086	0.103	0.122
30	0.097	0.116	0.137
36	0.108	0.126	0.150

Case depth = $0.025\sqrt{t}$ for 1700 F; $0.021\sqrt{t}$ for 1650 F; $0.018\sqrt{t}$ for 1600 F

For normal carburizing (saturated austenite at the steel surface during time at temperature)

Values of case depth calculated for three common carburizing temperatures are given in Table VI.

When carburizing is purposely controlled to produce surface carbon concentrations somewhat less than saturated austenite, the case depth will be slightly less than shown by the Harris equation. The case depth determined by the equation is total case depth and for case depths in the range from 0.040 to 0.070 in. will correspond to a point on the carbon gradient where the carbon concentration is about 0.07% C higher than the carbon content of the core.

In addition to the time at carburizing temperature, several hours may be required for bringing the work to operating temperature. For work quenched directly from the carburizer, the cycle may be further lengthened to allow time for the work to cool from carburizing temperature to a quenching temperature of perhaps 1550 F. Although some diffusion of carbon from case to core occurs during this time, diffusion is slower than it would be at the carburizing temperature. This period may be used deliberately as a moderate diffusion period to lower the carbon concentration at the surface by maintaining an atmosphere of low carbon potential in contact with the work during this time.

F. E. Harris has also developed a method for calculating the carburizing time and diffusion time to produce a carburized case of predetermined depth and carbon concentration at the surface (Metal Progress, Aug 1943). This method is most adaptable to batch-type equipment. Successful application requires a well-conditioned furnace and a carrier gas of low carbon availability. All carbon additions are assumed to be made during the carburizing cycle when carrier gas and hydrocarbon gas are both supplied to the chamber. After the hydrocarbon addition to the carrier gas has been discontinued and the diffusion cycle started, it is assumed that no further carbon additions to the steel are made, either from the carrier gas or from hydrocarbon gas evolved from the furnace lining.

$$\text{Carburizing Time} = \text{Total Time}\left(\frac{C - C_i}{C_s - C_i}\right)^2$$

and

$$\text{Diffusion Time} = \text{Total} - \text{Carburizing Time}$$

where total time, in hours, is calculated from the equation in Table VI, C is the final desired surface carbon concentration, C_s is the surface carbon concentration at the end of the carburizing cycle, and C_i is the concentration of carbon at the core.

Control of Atmosphere

In addition to supplying available carbon for the carburizing reaction, the hydrocarbon gases may also increase the carbon potential of the atmosphere within the carburizing chamber by decreasing the dew point (% H_2O) and the CO_2 content in accordance with the following reactions:

$$CH_4 + H_2O = CO + 3H_2$$
$$CH_4 + CO_2 = 2\,CO + 2H_2$$

These reactions are relatively slow, however, and many times more methane is required than would be necessary to produce an equivalent decrease in the dew point and CO_2 content by increasing the gas-air ratio to the generator where the reactions occur at a higher temperature in the presence of a catalyst.

It is not advisable to supply a carrier gas of high dew point and CO_2 content to the furnace and attempt to "clean up" the atmosphere within the carburizing chamber, since extraneous reactions may occur at the surface of the steel which can produce entirely unpredictable results. For a well-controlled operation it is preferable to produce a carrier gas of a composition that will be approximately in equilibrium with the desired surface carbon concentration at the carburizing temperature employed (see page 141).

The carbon potential of atmospheres can be decreased readily within the carburizing chamber by metering small amounts of air to increase the dew point (% H_2O) and the CO_2 content by the reactions:

$$CO + \tfrac{1}{2}\,O_2 = CO_2$$
$$H_2 + \tfrac{1}{2}\,O_2 = H_2O$$

These reactions occur very rapidly. Such a procedure has been used successfully for reducing the carbon potential in the last zone of continuous carburizers in order to obtain a diffusion period with a consequent decrease in surface carbon concentration.

For carburizing to surface carbon concentrations in the range of 0.80 to 1.00% C, using endothermic carrier gas, it is common practice to produce the carrier gas in the range of +10 to +30 F dew point. Hydrocarbon additions sufficient to produce the desired carbon potential and availability are mixed with the carrier gas before it enters the furnace. Producing carrier gas of dew point lower than +10 F causes accelerated sooting of the generator catalyst and necessitates frequent burnouts.

For low surface carbon concentrations, often required for homogeneous carburizing, the air-gas ratio supplied to the generator may be adjusted to give dew points higher than +30 F. Equilibrium curves are of considerable value for establishing and controlling the atmosphere to obtain desired surface carbon concentrations (see page 141).

Undiluted hydrocarbon gases or liquids are normally applied only to batch furnaces with good seals for doors and covers, and fans for recirculation. Normally when carburizing with straight natural gas or hydrocarbon liquids, it is difficult to regulate the atmosphere except by providing conditions that will result in saturated austenite at the carburizing temperature. In many applications such high surface carbon may result in too much retained austenite after quenching. To obtain a lower surface carbon content, and a carbon gradient that is not too steep, a diffusion cycle is run at the carburizing temperature. This is done either by stopping the flow of hydrocarbon gas or liquid or by decreasing the flow so that an atmosphere of reduced carbon potential is maintained in the furnace during the diffusion cycle.

Whether the flow of carburizing fluid is completely stopped or decreased to some minimum flow to maintain a certain partial pressure in the furnace depends on the seals of the furnace and the degree of infiltration. Usually when undiluted hydrocarbon gases or liquids are being used, it is difficult to carburize without deposition of soot on the work and in the furnace. Stopping the flow of atmosphere during the diffusion cycle often permits the soot to be burned off the work with the infiltrating air to form a carbon monoxide-nitrogen atmosphere of decreased carbon potential. The carbon potential must not be reduced too much.

Homogeneous Carburizing

Both the "carburizing - diffusion" method and the "starved carbon" or "balanced atmosphere" method are being used in production for a special carburizing application known as "homogeneous carburizing". In this process parts of relatively small cross section are carburized throughout the section to a nearly constant carbon content. This process offers the advantage of making a part, such as an intricate stamping, from an easily formed low-carbon steel and then carburizing throughout to a carbon content that will provide the desired hardness after heat treatment. The balanced atmosphere procedure may be used with parts that have considerable variation in section; carburizing-diffusion is limited to parts having approximately uniform cross sections.

Gas Carburizing

Part II — Application of Equilibrium Data

By the ASM Committee on Gas Carburizing

Reactions **140**

Carbon Availability and Carbon Demand **141**

Dew Point Control **142**

Infrared Analyzers **143**

Hot Wire Analyzer **143**

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THE IMPORTANT REACTIONS occurring in gas carburizing are:

$$CH_4 = (C) + 2\,H_2 \qquad (1)$$

$$2\,CO = (C) + CO_2 \qquad (2)$$

$$CO + H_2O = CO_2 + H_2 \qquad (3)$$

where (C) is carbon dissolved in austenite.

Reactions (1) and (2) indicate the addition of carbon to steel from methane and carbon monoxide to form a solution of carbon in austenite and the formation of hydrogen and carbon dioxide, respectively. Both of these reactions are reversible and the percentages of H_2 and CH_4, and of CO_2 and CO, required to maintain equilibrium with a particular surface carbon concentration in a given steel at a definite temperature can be calculated from thermochemical data.

The equilibrium data shown in Table I and Fig. 1 to 3 can be used readily without detailed knowledge of the thermochemical data used to establish them. However, a brief discussion of the principles involved may prove helpful for calculating equilibrium data for special conditions not covered here. The following equilibrium constants are from the work of F. E. Harris (Metal Progress, Jan 1945).

For reaction (1):

$$\text{Log } K = \frac{8370}{T} - 5.770 \qquad (1\text{-A})$$

For reaction (2):

$$\text{Log } K = \frac{-15{,}966}{T} + 9.060 \qquad (2\text{-A})$$

where T is the absolute temperature, in degrees Rankine (deg Fahr + 460) and K is the equilibrium constant.

For the hypothetical reversible reaction $aA + bB = cC + dD$, in which "a" unit volumes of gas A react with "b" unit volumes of gas B to produce "c" unit volumes of gas C and "d" unit volumes of gas D.

$$K = \frac{(\text{par pres of A})^a \times (\text{par pres of B})^b}{(\text{par pres of C})^c \times (\text{par pres of D})^d}$$

where the partial pressure (par pres) of each gas is equal to the pressure of the system multiplied by the volume fraction of the gas.

Both reactions (1) and (2) involve a consideration of the iron-carbon diagram. In the gas system the partial pressure for saturated austenite is taken as unity, and for all carbon concentrations less than saturation it is assumed to be proportional to the degree of saturation. This assumption of straight-line activity leads to no great error. The carbon content of saturated austenite varies with steel composition as shown in Fig 4. The data of Table I and the equilibrium curves of Fig. 1 to 3 have been calculated for plain carbon steel, but can be used with equal accuracy for low-nickel steels such as those in the series 4100, 8600 and 8700 and with slightly less accuracy for 4300, 4600 and 4800 grades. For the same atmosphere and temperature the equilibrium carbon concentration for 4300 and 4600 series steels will be about 5% lower than for 1020, and for 4800 steels will be about 10% lower than for 1020.

Supplements the article on page 678 of the 1948 ASM Metals Handbook

The manner in which equilibrium data are calculated can be illustrated by an example. For this example, the CO_2 and CO percentages that will maintain a 1.0% carbon concentration at the steel surface at 1650 F will be determined.

When applying equation (2-A), an activity or percentage saturation factor A must be employed in calculating equilibrium gas concentrations for carbon levels below saturation. Taking the saturated austenite composition of the steel at 1650 F to be 1.18%, then the activity or degree of saturation = A = 1.00/1.18 = 0.847. The total pressure will be essentially one atmosphere and the partial pressure of the $CO\text{-}CO_2$ system will be chosen as 0.2 atm, that is:

$$\frac{\%CO + \%CO_2}{100} = 0.2 = P$$

Let the volume fraction of CO in the $CO\text{-}CO_2$ system = X and the volume fraction of $CO_2 = 1 - X$.

From equation (2-A):

$$\text{K} = 31.0 \text{ at } 1650 \text{ F } (2110 \text{ R})$$

$$\text{K} = 31.0 = \left(\frac{1}{A}\right)\frac{(P \cdot CO)^2}{(P \cdot CO_2)} = \left(\frac{1}{A}\right)\frac{(PX)^2}{P(1-X)}$$

$$= \frac{P}{A}\left(\frac{X^2}{1-X}\right)$$

for which $X = 0.9925$

Actual % CO = 0.9925(0.2)100 = 19.85%

and $1 - X = 0.0075$

Actual % CO_2 = 0.0075(0.2)100 = 0.15%

This gives point A of the diagram for the $CO\text{-}CO_2$ system at 1650 F in Fig. 1.

The equilibrium percentages of CH_4 and H_2 in the $CH_4\text{-}H_2$ system that are shown in Table I were calculated in a similar manner. The areas of the chart

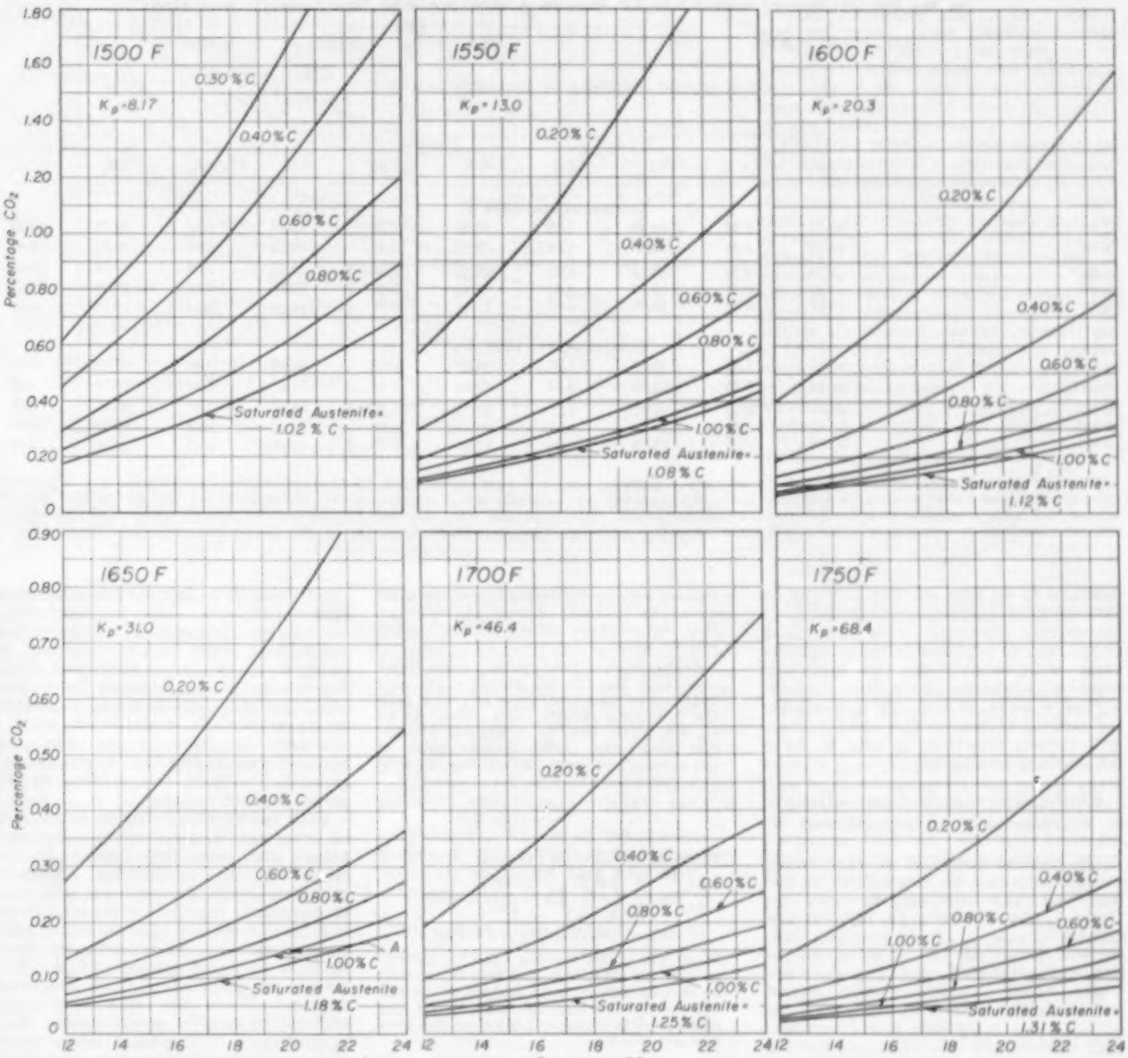


Fig. 1. Percentages of CO_2, and CO in Equilibrium with Various Carbon Concentrations in Plain Carbon Steel at Six Temperatures (W. T. Groves, Industrial Heating, June 1949)

bounded by the heavy lines represent the range of most commercial carburizing practices.

A definite relationship exists between the H_2O/H_2 ratio and the CO_2/CO ratio of furnace atmospheres in accordance with the water gas reaction:

$$CO + H_2O = CO_2 + H_2 \qquad (3)$$

This reaction, like reactions (1) and (2), is reversible and the relative proportion of each gas existing at equilibrium is a function of temperature, as shown by the following relation:

$$\text{Log } K = \frac{-3175}{T} + 1.627 \qquad (3\text{-A})$$

$$K = \frac{(CO)(H_2O)}{(CO_2)(H_2)} \text{ or}$$

$$\frac{(H_2O)}{(H_2)} = K\left(\frac{CO_2}{CO}\right)$$

The equilibrium constant for the water gas reaction given above was calculated by F. E. Harris from data by Wagman, Kilpatrick, Taylor, Pitzer and Rossini (Jour Res, NBS, 34, 143, 1945).

Since no volume change occurs during the reaction, the equilibrium concentrations are not dependent on the pressure at which the reaction occurs. It is evident that at any particular temperature the H_2O/H_2 ratio differs from the CO_2/CO ratio only by a constant. Values of the equilibrium constant *K* at different temperatures are given in Table II.

Carbon Availability and Demand

From the equilibrium values of H_2 and CH_4 shown in Table I it can be seen that CH_4 is a very strong carburizing gas while H_2 is a weak decarburizing gas. At 1700 F and a partial pressure of 0.4 atm (% CH_4 + % H_2 = 40% of total gas mixture) it is seen that only 0.20% CH_4 is required to be in equilibrium with 39.80% H_2 to maintain a saturated austenite composition at the steel surface. All the CH_4 in excess of 0.20% is available for carburizing. By making the assumption that all the methane is available for adding carbon to the steel surface C. H. Leland has shown how to calculate the minimum amount of methane required to produce a predetermined case depth in a batch-type work load of known surface area (Metal Progress, June 1949). Since the over-all carburizing efficiency will not be 100%, flows of methane or equivalent hydrocarbon must be employed that are 50 to 100% in excess of the calculated minimum, as experience dictates for the specific application.

In contrast with the high availability of carbon from methane in the CH_4-H_2 system, an inspection of Fig. 1 indicates that CO is a very weak carburizing gas and that CO_2 is strongly decarburizing. At 1700 F and a partial

Table I. Concentrations of CH_4 and H_2 in Equilibrium with Various Surface Carbon Concentrations, for Partial Pressures of the CH_4–H_2 System from 0.2 to 1.0 Atm, in Accordance with Equations (1) and (1-A)

$$CH_4 = (C) + 2\,H_2 \ldots\ldots\ldots (1) \qquad \text{Log } K = \frac{8370}{T} - 5.770 \ldots\ldots\ldots (1\text{-A})$$

$$\text{where (C) is carbon dissolved in austenite and } K = \frac{CH_4}{PA\,(H_2)^2}$$

Pressure, P, atm	Saturated Austenite		1.00% C		0.80% C		0.60% C		0.40% C	
	$\%H_2$	$\%CH_4$	$\%H_2$	$\%CH_4$	$\%H_2$	$\%CH_4$	$\%H_2$	$\%CH_4$	$\%H_2$	$\%CH_4$
Temperature, 1600 F										
1.00	98.12	1.88	98.30	1.70	98.63	1.37	98.97	1.03	99.31	0.69
0.80	78.77	1.23	78.91	1.09	79.12	0.88	79.34	0.66	79.55	0.45
0.60	59.30	0.70	59.38	0.62	59.50	0.50	59.62	0.38	59.75	0.25
0.40	39.69	0.31	39.72	0.28	39.78	0.22	39.83	0.17	39.88	0.12
0.20	19.92	0.08	19.93	0.07	19.94	0.06	19.96	0.04	19.97	0.03
Temperature, 1700 F										
1.00	98.75	1.25	99.00	1.00	99.20	0.80	99.40	0.60	99.60	0.40
0.80	79.20	0.80	79.36	0.64	79.48	0.52	79.61	0.39	79.74	0.26
0.60	59.54	0.46	59.63	0.37	59.70	0.30	59.78	0.22	59.85	0.15
0.40	39.80	0.20	39.84	0.16	39.87	0.13	39.90	0.10	39.93	0.07
0.20	19.95	0.05	19.96	0.04	19.96	0.04	19.97	0.03	19.98	0.02

P is the partial pressure of the CH_4-H_2 system expressed in atmospheres and listed in column 1 of this table. For applications where the total pressure is approximately equal to 1 atm, this will be numerically equal to $(\%CH_4 + \%H_2)/100$. A is the activity of carbon in steel, or the percentage saturation, and is numerically equal to the actual percentage of carbon at the surface of the steel divided by the percentage of carbon corresponding to saturated austenite at the particular temperature employed.

pressure of 0.2 atm (% CO + % CO_2 = 20% of total gas mixture), common in carburizing furnaces, it is seen that 19.92% CO is required to be in equilibrium with 0.08% CO_2 to maintain saturated austenite at the steel surface. Virtually none of the CO is available for adding carbon to the steel surface and carbon monoxide is said to have low carbon availability.

Evaluating and Controlling Carburizing Atmospheres

The carbon potential of carburizing atmospheres can be determined on the basis of gas composition with an Orsat analyzer (see page 145), a dew point indicator, or an infrared analyzer. Carbon potential can also be determined directly with a hot wire analyzer.

Dew Point. A commonly used method of evaluating and controlling furnace atmospheres is by dew point readings, and instruments are available for recording and controlling the dew point automatically. Dew point measurements have some advantage over CO_2 analysis by the Orsat method for an atmosphere that is basically of the 302 type. The 302 type atmosphere has H_2 and CO contents of approximately 40 and 20% respectively. The percentage error resulting from a check on the H_2-H_2O system will be considerably less than the percentage error of the check on the CO-CO_2 system, other things being equal.

In addition, the H_2O values as indicated by dew points may be spread over a fairly broad range whereas corresponding CO_2 values as determined by the Orsat method are confined to the zero end of the scale where an error of ±0.05% may be of considerable consequence. Dew point is plotted against percentage H_2O by volume in Fig. 2.

The use of Fig. 1 and 2 and Table II for evaluating furnace atmospheres will be illustrated by the following two examples:

Example 1. Orsat analyses of the effluent gas of a carburizing furnace operating at 1650 F indicate 0.15% CO_2 and 19% CO. It is desired to predict the surface carbon concentration of the steel being carburized. Figure 1 indicates that the surface carbon concentration will be 0.9%.

Example 2. Dew point and Orsat checks on the effluent gas of a gas carburizing furnace operating at 1700 F give the following results: dew point, 22 F; H_2, 40%; CO, 20%. It is desired to predict the surface carbon concentration of the carburized stock. From Fig. 2, 22 F dew point = 0.39% H_2O by volume.

$$\frac{H_2O}{H_2} = \frac{0.39}{40} = 0.00975$$

From Table II, $K = 1.44$ and

$$\frac{CO_2}{CO} = \frac{1}{K}\left(\frac{H_2O}{H_2}\right) = \frac{0.00975}{1.44} = 0.00676$$

$$CO_2 = (20)(0.00676) = 0.135\%$$

From the curve for the CO-CO_2 system in Fig. 1, 0.135% CO_2 and 20% CO should be in equilibrium with a steel of carbon content 0.80%, and this should be the surface carbon concentration of the carburized stock.

It should be recognized that the above calculations apply to equilibrium conditions. True equilibrium conditions seldom, if ever, exist in commercial carburizing. The calculated figures will agree best with results obtained in batch furnaces during long heat treating cycles. Such furnaces have reasonably tight chambers and a positive pressure can be maintained with a relatively low flow of gas. Also, the batch furnace employs a single and generally uniform temperature in the carburizing chamber.

With continuous furnaces there may be appreciable discrepancies between actual and calculated figures. In the operation of continuous furnaces relatively large flows of gas are used to maintain chamber pressure. There is a greater danger of atmosphere contamination and extraneous reactions in such furnaces because of the frequency of charging of work and door openings. There may be a wide range of temperature in a continuous furnace, varying from a black temperature just inside the charge door to 1700 F in the carburizing chamber, to 1550 F or lower in the zone just before discharge. Also the composition of the influent gas supplied to different zones of the furnace may be purposely varied, as is mentioned on pages 136 and 137. Under such conditions a gas analysis in only one zone of the furnace will not indicate accurately the surface carbon concentration of the discharged work.

Because of the greater accuracy of dew point measurements compared with CO_2 contents determined by Orsat, the dew point method is being used increasingly for control work. The solid curves of Fig. 3 illustrate the relationship between dew point, surface carbon concentration and temperature for an atmosphere where H_2 = 40% and CO_2 + CO = 20%. Such percentages might exist in a furnace supplied by endothermic gas from a generator that used natural gas as a base fuel. The curves were plotted from data of Fig. 1 and 2. The shaded areas indicate the correlation actually obtained in investigations conducted independently by O. E. Cullen (Metal Progress, Dec

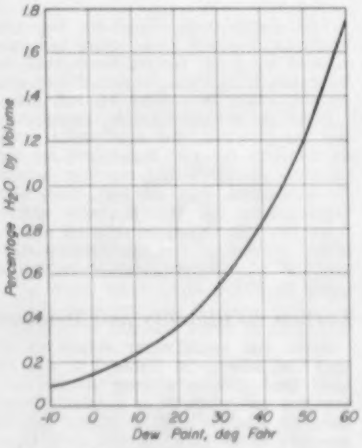


Fig. 2. Dew Point Versus Percentage H_2O by Volume

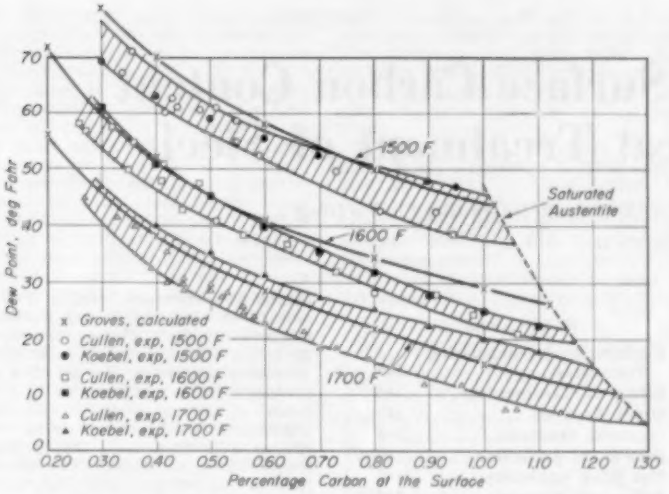


Fig. 3. Dew Point Versus Surface Carbon Concentration at Temperatures Indicated. Solid lines show calculated theoretical relationships for atmosphere with 40% H_2 and 20% total CO and CO_2. Shaded area indicates correlation obtained experimentally by two investigators with atmospheres which approximated *the same conditions.*

1953) and N. K. Koebel (Metal Progress, Feb 1954) with atmospheres that approximated the condition of % H_2 = 40 and % CO_2 + % CO = 20. Cullen's test points were obtained with a laboratory furnace employing straight endothermic generator gas and also with large continuous gas carburizing production furnaces using endothermic generator gas plus normal hydrocarbon additions. Koebel's data were determined in a laboratory furnace using straight endothermic generator gas.

It must be noted that dew point in itself has no significance with regard to carbon equilibriums unless the other components of the water gas reaction, H_2, CO_2 and CO, are also evaluated. It should be emphasized that the theoretical curves in Fig. 3 were plotted from data calculated for the specific conditions in which H_2 is 40% and CO + CO_2 = 20%. For calculating surface carbon concentrations in equilibrium with atmosphere compositions other than this, Fig. 1 and 2 should be used as illustrated in examples 1 and 2.

Infrared Analyzers are available for providing continuous records of methane and carbon dioxide contents with accuracies not possible heretofore. For example, CO_2 analyzers can be obtained having ranges as low as 0 to 0.5% which are sensitive, stable and reproducible to ±0.005% CO_2, and similar accuracies can also be obtained for methane. The speed of response is from 5 to 10 sec, depending on the length of sample line. This permits the use of automatic control for furnaces or generators if desired.

The use of dew point recorders and infrared analyzers therefore permits full utilization of equilibrium curves as operating guides in addition to permitting automatic control of furnaces and generators. They likewise furnish a continuous record of furnace or generator performance and alert the operators in the event of any abnormal conditions that would affect the quality of the product adversely.

Table II. Values of Equilibrium Constant, K, at Various Temperatures for the Water Gas Reaction

$$CO + H_2O = CO_2 + H_2 \ldots\ldots (3)$$

$$\text{Log } K = \frac{-3175}{T} + 1.627 \ldots\ldots (3\text{-A})$$

$$K = \frac{(CO)\,(H_2O)}{(CO_2)\,(H_2)}$$

$$\frac{(H_2O)}{(H_2)} = K \left(\frac{CO_2}{CO}\right)$$

Temperature deg Fahr	K
1750	1.55
1700	1.44
1650	1.33
1600	1.22
1550	1.12
1500	1.02

The Hot Wire Analyzer operates on the principle that at elevated temperatures the electrical resistance of iron and iron alloys changes with carbon content. An iron alloy primary element is inserted into the furnace work chamber and furnace atmosphere is continuously drawn past it. A continuous record is obtained directly in terms of percentage carbon. The usable operating range of the analyzer is from 0.15 to 1.15% C and the normal accuracy is ±0.05% C. This equipment is normally furnished for completely automatic control. Since the primary element is sensitive to all contaminants carried into the furnace with the work and work containers these metal parts and fixtures must be chemically clean. At present, the hot wire analyzer is furnished only for use with furnaces that are made by the manufacturer of the analyzer.

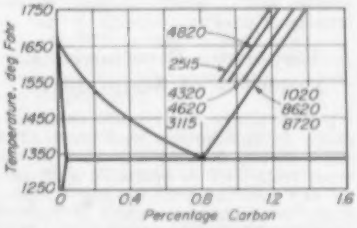
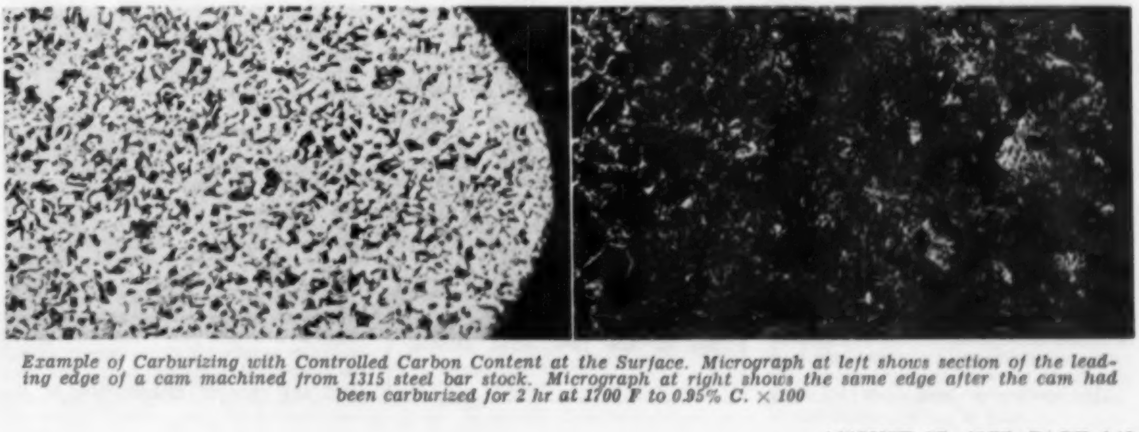


Fig. 4. Approximate Solubility of Carbon in Austenite for Eight Steels (F. E. Harris)

Conclusion. Because of the variance in commercial carburizing practice throughout industry, with consequent varying deviations from equilibrium conditions, it is evident that there can be no single set of data, either theoretical or practical, that will correlate with all operating results. The equilibrium curves presented here give a useful correlation for most operations. Knowledge of the fundamental principles is of value for intelligent application of controlled atmospheres to any set of furnace conditions and heat treating requirements.



Example of Carburizing with Controlled Carbon Content at the Surface. Micrograph at left shows section of the leading edge of a cam machined from 1315 steel bar stock. Micrograph at right shows the same edge after the cam had been carburized for 2 hr at 1700 F to 0.95% C. × 100

Control of Surface Carbon Content in the Heat Treatment of Steel

By the ASM Committee on Gas Carburizing

Subdivisions

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ASM-SLA J, TS, SS, ST

CONTROL of the surface carbon content of steel through control of the surrounding furnace atmosphere is most common in carburizing, homogeneous carburizing, carbon restoration and hardening. Less common applications include tempering and annealing. Carbon control is used also for the surface protection of tool, die and cutlery steels; in the sintering of iron-carbon powder metal compacts; and in the brazing of steel products.

Carburizing-Decarburizing Potentials of Atmospheres

Heat treating may require an atmosphere in equilibrium with steel of a given carbon content anywhere in the range from 0.1% to saturated austenite, for any specified heat treating temperature. Such carbon control is difficult unless controllable amounts of both carburizing and decarburizing constituents are present in the atmosphere. The carburizing-decarburizing tendencies of the three principal reactions are:

Carburizing→ ←Decarburizing

$$\begin{aligned} CH_4 &= (C) + 2\,H_2 \\ 2\,CO &= (C) + CO_2 \\ CO + H_2 &= (C) + H_2O \end{aligned}$$

in which (C) represents carbon dissolved in austenite.

An approximate classification of the carburizing-decarburizing tendencies of the principal types of heat treating atmospheres is shown in Table I.

More specific data on the relationships among composition of atmosphere, surface carbon concentration of plain carbon steels, and temperature are given in Fig. 1 on page 141. Fig. 3 of that article shows the relations among dew point, surface carbon of plain carbon steels and temperature for a typical endothermic atmosphere.

The most common atmosphere for carbon control work is the endothermic class 302. Control of the carbon potential of this atmosphere can be maintained over a wide range by control of the ratio of hydrocarbon gas to air at the generator.

Less commonly employed for carbon control work are the prepared nitrogen-base class 201 and the charcoal-base class 402 atmospheres.

When employed in muffle furnaces where low dew points can be maintained, the ammonia-base class 501 atmosphere is successfully used in carbon control applications such as the heat treatment of tool steels and martensitic or austenitic stainless steels. Hydrocarbon gas must be added to obtain a carburizing potential in this atmosphere. Sometimes, hydrogen-base atmospheres are similarly employed.

The exothermic-base class 101 and 102 atmospheres are least commonly employed because of the difficulty of maintaining a controlled carbon potential for any steels except those of very low carbon content. Some degree of control can be attained, however, by drying these atmospheres and making hydrocarbon additions.

Effect of Temperature

The simplest problem of carbon control exists when heat treating is being done at one temperature in the austenite region. Under these conditions satisfactory carbon control has been obtained with the common practice of measuring one constituent, such as dew point or CO_2.

Some slight additional problems arise when carbon control is attempted during heat treating cycles that involve different temperatures in the austenite region. Any change in temperature requires a corresponding change in the atmosphere if carbon is to be maintained at a constant level or if it is to change in a specified way during the temperature shift. The usual procedure in batch furnaces is to establish the necessary changes in dew point or other control variable and then, using a "program" or manual control, to adjust the atmosphere continuously or in closely spaced steps to provide the proper atmosphere to accompany the temperature or carbon changes that may be required by the process.

Supplements the article on page 294 of the 1948 ASM Metals Handbook

Figure 1 gives approximate dew point aims recorded by one company as a guide for various production steels and for an atmosphere of the endothermic class 302, in the temperature range from 1500 to 2100 F.

Although infrequent in normal heat treating, the most difficult problem of carbon control occurs when steel is being held within the transformation range (between A_3 and A_1) or below A_1. In these regions of mixed phases (ferrite-austenite and ferrite-cementite, respectively) the equilibrium between atmosphere and steel is based on the maximum solubility of carbon in ferrite and is independent of the relative amounts of phases present. Fast heating or cooling allows considerable leeway in ratios or dew points, but extended times below or within the transformation range will result in a noticeable increase or decrease in total carbon when the atmosphere is not in proper balance.

In the single-phase ferrite area where the solubility of carbon in iron is less than 0.03%, control conditions are identical, in principle, with the single-phase austenite area. Carbon content depends on definite CO-CO_2 and H_2-H_2O ratios, or dew point, for every temperature. This low-carbon range is very limited in application and seldom is a consideration in practical problems of carbon control.

In practice, for most heat treating operations, including carburizing, hardening, carbon restoration and homogeneous carburizing, the heating up portion of the cycle is relatively short, and the lack of carbon control during this period is a negligible factor. Furthermore, any slight effects are erased by subsequent control in the austenite range. However, when large masses of steel are being heat treated, the heating portion of the cycle may be equal to or longer than the austenitizing portion, and it becomes more important to consider the carbon potential of the atmosphere during this time. Generally, this type of processing is done in large batch furnaces and the atmospheres are usually controllable mixtures of relatively neutral gases such as nitrogen plus carburizing gases. In such applications, the operation can be controlled by programming the time and the rate of introduction of the active carburizing gas to correspond with temperature and the degree of atmosphere contamination in the furnace from the furnace load.

When steel is being heated, decarburizing gases are generated. For best control of carbon it is advisable to sweep these gases out at temperatures low enough to prevent or minimize their decarburizing effects. It is usually advisable to heat steel in relatively inert atmospheres up to about 1200 F and then to hold at this temperature until the decarburizing gases have been evolved and swept from the furnace chamber. Thereafter, carbon-controlling gases are added to the neutral gas at an increasing rate during the remainder of the heating cycle, or the inert gas is completely replaced by endothermic atmosphere at some intermediate stage.

During the cooling portion of a cycle, the composition of the atmosphere may be altered, usually by cutting off the carbon controlling atmosphere gradually or entirely. Inert atmosphere is used for replacement.

In cycle annealing treatments in continuous furnaces where the steel is cooled to below A_1 and held, the carbon potentials in the different temperature zones of the furnace are controlled by baffles between zones and by roof arches and solid-bottom piers, with various predetermined mixtures of inert and active carbon-controlling gases introduced into the different zones.

Instruments for Evaluating and Controlling Atmospheres

The correlation of carbon potential with gas composition requires rather precise knowledge of the content of CO_2, CH_4 or H_2O in the gas. Four principal methods are used for obtaining this information.

Orsat Analysis. For many years the most common equipment used for determining composition of furnace atmospheres has been the Orsat analyzer. Such equipment can be used for analyzing the gas for CO, CO_2, CH_4, H_2, O_2 and N_2. The CO, CO_2 and O_2 contents are determined by absorption in selective chemical reagents, and the CH_4 and H_2 contents by combustion with O_2 and then absorption of the CO_2 and condensation of the H_2O. The N_2 is determined by difference. The apparatus may be used only for individual checks of each gas component.

The time for analysis will vary from 5 min, for determining the CO_2 content only, to about 30 min for a determination of the entire gas composition. The accuracy will vary from about ±0.05 to ±0.2%. The Orsat analyzer is relatively inexpensive both for the simplest form and for the precision type.

While the Orsat analyzer has its place in gas analysis, it is often unsuitable for production applications because it does not yield a continuous measurement and has relatively low accuracy compared with that required for carbon control of atmospheres.

Infrared Analyzers may be used for the continuous measurement of CO_2, CO and CH_4. These analyzers operate on the selective absorption of infrared energy and utilize two fundamentals:

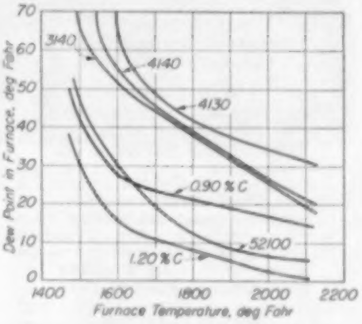

Fig. 1. Example of Relationship Between Production Steels, Alloy and Carbon, and Dew Point of Endothermic Atmosphere in a Production Application

1. Each gaseous compound absorbs a certain portion of the infrared radiation that no other gas absorbs.
2. The amount of radiation absorbed is proportional to the concentration of the gaseous compound.

These analyzers are available from several manufacturers and are obtainable in multiple-point arrangements. Extremely high accuracy of measurement is possible. For example, a full range of 0 to 0.5% CO_2 will produce a sensitivity, stability, reproducibility and readability of 0.005% CO_2. The speed of response will depend on the flow rate of the sample but normally is from 5 to 10 sec. These analyzers lend themselves to production applications and can be used for automatic control of the atmosphere composition.

Table I. Approximate Carburizing-Decarburizing Tendencies of Principal Types of Heat Treating Atmospheres

AGA Class	Type	Carburizing Activity
101	Exothermic base	Decarburizing
102	Exothermic base	Decarburizing to 0.10% C and above
201	Prepared nitrogen base	Neutral to decarburizing, depending on purity
302	Endothermic base	Carburizing up to 0.60 to 0.80% C, depending on composition
402	Charcoal base	Decarburizing or carburizing, depending on composition
501	Ammonia base	Neutral to decarburizing, depending on composition
...	Hydrocarbon gases such as natural gas, city gas, propane or butane	Highly carburizing and difficult to control in undiluted form

For typical compositions of types 102, 201, 302 and 402, and the hydrocarbon gases, see Tables I and II in the article "Gas Carburizing", page 133. On the same basis as Table II, page 133, and from the source quoted there: class 101 has 86.8% N_2, 1.5% CO, 10.5% CO_2 and 1.2% H_2; class 501 is commercial dissociated ammonia (dew point, −60F).

To aid in controlling carbon potential over wide ranges, measured quantities of hydrocarbon gas may be added to classes 201, 302, 402 or 501.

Dew Point Analyzers are available from several manufacturers and may be of either the indicating or recording type, in single or multiple-point arrangements. Three different principles or methods of operation are in use:

1. Condensation of water on a cooled, polished metal or mirror surface
2. Formation of fog by sudden expansion of compressed gas
3. Change in resistivity of salt compounds by variation in the moisture content

The first method is available either as an indicator or as a recorder. It requires a means for cooling the condensing surface and a means for evaporating the condensed vapor. Supercooling (too rapid cooling) must be avoided because it will produce erroneous readings. The gas sample must be kept clean, or maintenance of the polished surface will be excessive. The method is also subject to errors from condensable organic compounds that may be present in the gas. The recording type produces essentially a continuous record and may be used as a controller even though several minutes elapse between alternate condensations and evaporations.

The second method (formation of fog) is used as an indication only. Instruments available are readily operated and require little maintenance.

The third method (resistivity of salts) is available as a recorder or as a recorder-controller, single or multiple point. For application to heat treating atmospheres, the gas sample is normally cooled by refrigeration to permit attainment of the equilibrium temperature in the sensing element. This system provides a true, continuous record of atmosphere composition, since alternate condensation and evaporation are not involved.

Accuracy of dew point analyzers is from ±2 to ±5 F.

Hot Wire Analyzers operate on the principle that at elevated temperatures the electrical resistance of iron and iron alloys changes with the carbon content. The iron alloy primary element is inserted into the furnace work chamber and operated continuously. The furnace atmosphere is drawn past the primary element so that it reflects the carbon potential the same as the work being processed.

Since the carburizing reaction is reversible, the primary element is sensitive to changes in carbon potential in the atmosphere, and a continuous record is obtained directly in percentage of carbon. Means are provided for temperature compensation so that the carbon potential may be recorded directly at temperatures in the range from 1450 to 1750 F. Means are also provided for automatic calibration so that chemical analyses of steel specimens are not necessary for calibration. The usable operating range of the analyzer is from 0.15 to 1.15% C. The normal accuracy, including all variables is ±0.05% C. This equipment is normally furnished for complete automatic control.

Since the primary element is sensitive to all contaminants carried into the furnace, both the work and its containers must be chemically clean. Most of the contaminants that would affect the primary element adversely, such as cleaning fluids, alkalis, sulfur-bearing oils, lead compounds and the like, will also affect the quality of the treatment or the furnace alloy in time.

The principal limitation, at present, is that the analyzer is furnished only for use with furnaces made by the manufacturer of the analyzer.

Automatic Control

The application of automatic control to furnaces and generators using the recording analyzers previously discussed requires careful engineering. The detection time for changes in the measured value must be minimized. This requires short sampling lines and rapid rates of sample flow. Some of the analyzers have relatively slow rates of response, which will increase the detection lag. As contrasted with temperature control, where the heat storage in the furnace insulation, alloy and metal work provides stabilizing effects, the control of furnace atmosphere is more difficult because there is no similar stabilizing influence. Therefore, the control equipment must be of the proportional-position or input-control type. Preferably it should be of the so-called "three-function" type—that is, proportional band, rate action, reset action. The final control element should be positionable to an accuracy of 1% or better.

On furnaces it is normally preferable that the flow of carrier gas be maintained constant and the flow of enriching gas be the controlled flow.

On generators, control can be obtained by having the final control element operating the ratio setting on the carburetor. Another method is to keep the air-gas mixture constant with the carburetor and to use a controlled valve in a bypass line around the carburetor. It is recommended also that the total gas flow to the generator be kept at a reasonably constant value and that the generated gas not used be vented to the air.

Sampling of Atmospheres

The sample must be taken from the furnace chamber as close as possible to the work being treated. Carbon or low-alloy steel sampling tubes will oxidize and cause erroneous readings. Permanent sampling tubes of stainless steel or a high-nickel alloy should extend through the furnace wall for at least 4 in., and should be of small diameter (⅜ to ½-in. ID if possible). A gas sample should never be taken next to a furnace shell without a tube extending through the refractory lining, because the sample will come from stagnant gas contaminated by moisture and reaction products from the refractories and in addition may be of greatly altered composition because of interreaction of the atmosphere constituents caused by the lower temperature near the outer wall of the furnace. It is desirable to draw the atmosphere directly from the hot zone and to cool it quickly to avoid this interreaction. For spot checks, a sampling tube can be inserted through a peepsight or small hole and placed near the work.

The choice of metal for the sampling line from the furnace to the instrument is also important. For permanent installations, stainless steel is preferred but copper tubing has been widely and successfully used where it is not exposed to furnace temperatures. Iron pipe may rust and a rusty layer may act as a sponge soaking up water vapor from a gas of high dew point and then slowly releasing it to a gas of low dew point, causing erroneous readings.

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For permanent sampling lines, a tee with a cleanout plug should be placed at the connection between the sampling tube and the furnace. Likewise, for cleaning purposes, tees or crosses with plugs should be placed at each 90-deg bend in the line. Even though the instrument may have a filter of its own, it is wise to install a separate filter about 2 ft from the gas sampling tube at the furnace to collect any soot or dirt. An ideal filter for this purpose is the type used for compressed-air lines, which has a replaceable porous metal filter cartridge and a transparent plastic bowl. Another common type utilizes glass wool as a filter cartridge. The filter cartridge can be observed and changed when dirty, and any condensate that may get into the filter can be observed and drained off by a petcock on the filter. If condensate is observed, the filter cartridge should be replaced by a new one. For dew point determinations it is extremely important to keep the lines dry and free from rust, soot or dirt that may absorb water vapor. If an intermittent sample is to be taken by a portable instrument, transparent synthetic tubing is ideal. The cleanliness of the inside of the tubing can be observed, and it does not contain any loose absorbent powder material, sometimes present in rubber tubing.

Before taking gas samples from a furnace chamber, enough time should be allowed for purging after the load is charged. This is particularly true when dew point is being used as a means of control. Abnormally high dew points, which occur immediately on starting up equipment or on charging a pit-type furnace in which the atmosphere has been burned out, will cause condensation of water in the sampling line and instruments, thereby preventing accurate dew point measurements until the line and instruments are dry. If continuous dew point instruments are used, a means should be provided for shutting off the sampling pump until the furnace has been conditioned properly. On batch furnaces, it would be desirable to do this automatically, with a limit switch and time-delay relay set for the proper purging time. When dew point is used as a means of carbon control, the sampling tube should never be water-cooled. This would cause condensation from gases of high dew point in the tube. With portable instruments, all air and stagnant gases must be purged from the sampling lines and instrument.

Safety. Because most furnace atmospheres used for carbon control are toxic and flammable, the gas sample should be either vented to the outdoors or burned. Some prefer to burn the exit gases, since the flame gives an indication of the proper flow for the instrument as recommended by the instrument manufacturer. For further discussion of safety precautions the reader may refer to page 134 of the article on Gas Carburizing.

Evaluating Carbon Control of Processed Parts

Five principal methods have been used for determining decarburization or carburization on processed parts and thus establishing the desirable operating range of carbon potential for a furnace atmosphere:

1 Hardness tests
2 Microscopic examination
3 Analysis of consecutive cuts
4 Analysis of shim stock or turnings
5 Change in weight

No one method can be recommended for all applications. For some applications, more than one of the five tests may be necessary to obtain the desired information or to verify or supplement one set of results.

Hardness Tests are simple to perform but are the least accurate for determining the extent of carburization or decarburization. One method of making a hardness test for decarburization is by grinding a series of adjacent cuts of 0.005 in. from the surface down through the subsurface. If the hardness increases on each successive subsurface cut, then the steel was decarburized, provided the steel was not of the kind that have a soft skin after carburizing.

The second method is to use a superficial hardness test in conjunction with the standard Rockwell hardness test. The values obtained are transposed by means of a conversion table to the Rockwell C scale. These values are compared with the value obtained from the

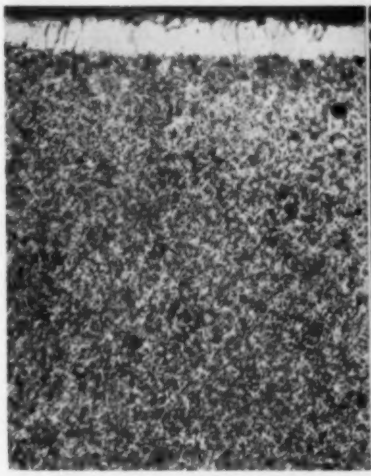

Fig. 2. Water-Hardening Carbon Tool Steel Hardened at 1450 F and Tempered at 700 F. Shows 0.0025 in. free ferrite but any decarburization that may be below this depth cannot be readily detected. Etched in nital. × 100

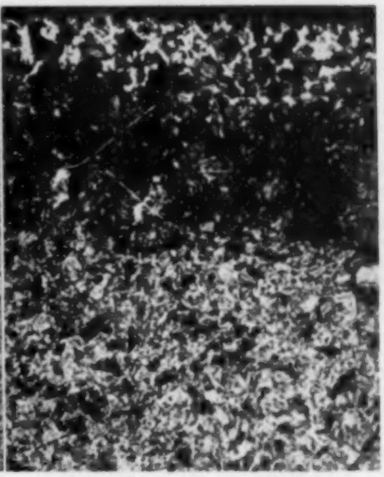

Fig. 3. The Same Specimen but After a Full Anneal to Define Decarburization. The hypereutectoid steel has been decarburized down to eutectoid carbon content or lower for a depth of 0.015 in. Etched in nital. × 100

standard test using the C scale. A lower transposed C value indicates decarburization. This method is more accurate than the first since it eliminates guesswork on specimens that are only a point or two over or under the maximum hardness of the steel. The test is useful also for checking tools or production work on which grinding would ruin the article. The method does not, however, detect decarburization or carburization that does not affect the hardness of the steel, nor will it distinguish between carburization and decarburization when both cause a soft skin.

The file hardness test is sometimes useful in detecting a soft skin which may not show up in the Rockwell hardness test. This test is subject to the human factor and is therefore much less reliable than the indentation tests made by machines.

One type of steel in particular that is susceptible to a soft skin when heat treated in a carburizing atmosphere is the 1% C, 5% Cr, 1% Mo type of air-hardening tool steel. Samples of this steel heat treated in neutral, decarburizing and carburizing atmospheres gave hardness results as follows: The hardness on the surface of the sample treated in the neutral atmosphere was Rockwell C 64, and verification by the change-in-weight method (described on page 148) showed the sample to be only very slightly decarburized, to −0.00005 g per sq cm.

The hardness of the sample treated in the decarburizing atmosphere was Rockwell C 58 on the surface but by the change-in-weight method, this sample was decarburized to −0.00172 g per sq cm. The sample heat treated in the carburizing atmosphere had a hardness of Rockwell C 50; the change-in-weight method showed this sample to be carburized to +0.00370 g per sq cm.

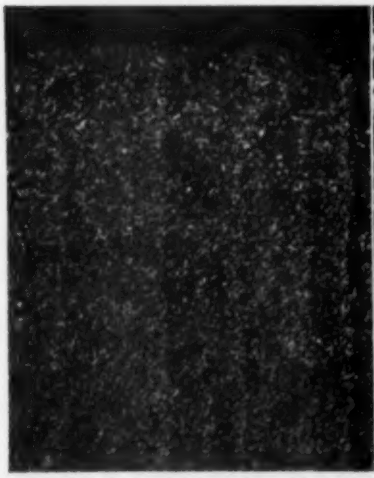

Fig. 4. Tungsten Chisel Tool Steel Hardened at 1750 F and Tempered at 700 F. The structure shows only slight decarburization but this steel was badly decarburized. Etched in nital. × 100

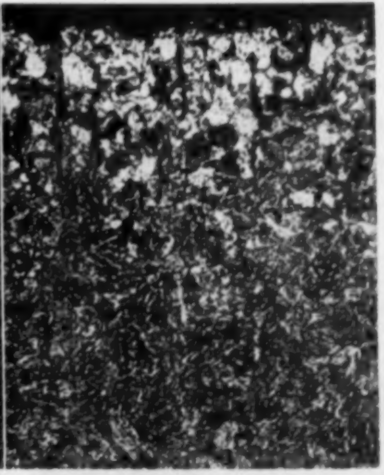

Fig. 5. The Same Chisel Steel Specimen but After a Full Anneal to Define the Decarburization. This shows the extensive decarburization that had actually taken place. Etched in nital. × 100

Microscopic Examination is common for determining decarburization or carburization, but false conclusions can easily be derived if one is not familiar with the limitations of the method. For example, Fig. 2 shows a decarburized surface on a water-hardening carbon tool steel of about 1.10% C. The band of free ferrite is about 0.0025 in. deep, but it is impossible to trace the total depth of decarburization below the free ferrite even though this specimen was tempered at 700 F to obtain a structure more likely to reveal decarburization than the as-quenched structure. Figure 3 (the same sample after a full anneal in purified nitrogen) shows that the area under the free ferrite was decarburized from a hypereutectoid steel down to a eutectoid steel and that the total depth of decarburization is about 0.015 in., instead of 0.0025 in., as would be inferred from Fig. 2. The free ferrite area is not the same in Fig. 2 and 3 because of the diffusion of carbon during annealing from the subsurface to the surface.

Figure 4, a tungsten chisel steel, 0.43% C, 1.66% W, 1.42% Cr, quenched from 1750 F and tempered at 700 F, shows only slight indications or traces of decarburization, but the steel was actually badly decarburized, as indicated by low hardness in the as-quenched specimen. Figure 5 shows the same piece after a full anneal in purified nitrogen; extensive decarburization is evident.

The best structure for detecting the depth of decarburization is obtained by full annealing. Unless the full anneal is carried out in the proper atmosphere, serious error may result because of decarburization or carburization during the annealing cycle. Unless the furnace atmosphere is being tested for annealing purposes, the specimen should *not* be annealed in the furnace atmosphere being tested, because decarburization may occur at lower temperatures that would not otherwise occur at the hardening temperature. It is better to quench the specimens and then anneal them in an atmosphere that is definitely known to be inert or neutral. The specimens may be copper-plated after hardening and then annealed.

Samples are frequently allowed to cool rapidly in the protective atmosphere. This is convenient but usually does not produce as good a structure as a full anneal for detecting decarburization. Cooling of samples in dry lime gives a rate of cooling slow enough to produce a satisfactory structure, and this method is sometimes used as a more convenient alternate to a full annealing treatment.

Even after full annealing, slight amounts of decarburization or carburization cannot always be detected. The best accuracy is obtained with carbon steels, but results from microscopic examination are never quantitative for plotting curves to compare the effects of atmospheres on various steels or to compare one atmosphere with another.

Chemical Analysis of Consecutive Cuts permits the plotting of results to show both the degree and depth of decarburization in terms of percentage of carbon. This method is also useful in the study of the effect of atmosphere on elements other than carbon.

The method may be carried out by using a test specimen about 6 in. long turned down to about 1 in. to remove original decarburization. After the specimen has been heat treated for the desired length of time, consecutive lathe cuts are taken to the point having the same carbon content as the original specimen. The depth of cut taken to obtain chips for each analysis is usually about 0.002 to 0.005 in. Deeper cuts may be taken as the core is approached. If the specimen is hardened from the atmosphere being tested, it must be annealed to obtain machinability. The analytical results are plotted as the mean distance of the layer from the surface of the specimen as shown in Fig. 6.

Analysis of Shim Stock or Turnings. Thin shim stock or stringer turnings of the type of steel to be tested in the furnace atmosphere are washed free from oil and placed in the furnace to be tested. Shims are preferred. Stringer turnings are difficult to clean, especially after carburizing when soot may be trapped in the fissures. Sufficient time is allowed for the atmosphere to come into equilibrium with the steel. With shim stock or turnings no thicker than 0.010 in., 2 or 3 hr should be sufficient. The specimens should not be oxidized or decarburized during the quenching operation. After the specimen has been cleaned carefully to remove all traces of oil and any free carbon, it is broken into chips of proper size and analyzed for carbon. The carbon in the chips is the carbon potential of the atmosphere. The shim stock method has the disadvantage of not showing the total depth or gradient of decarburization or carburization. However, it is ideally suited for checking the carbon potential of furnace atmospheres when the potential is below that of saturated austenite.

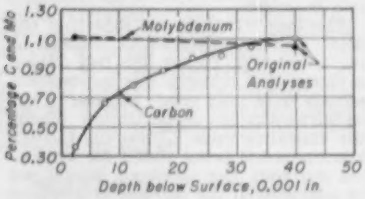

Fig. 6. Method of Plotting Results from Data Obtained from Chemical Analysis of Consecutive Cuts to Show Depth and Degree of Decarburization and the Effects of the Atmosphere on Constituents Other than Carbon in the Steel. For low-alloy, air-hardening tool steel with 1.10% C, 5.25% Cr, 1.04% Mo

The Change-in-Weight Method of determining decarburization or carburization is the most accurate of the five listed when applied to scale-free atmospheres, and provided the sample can be cooled in the furnace atmosphere. It is a research method, rather than a procedure for production control, and consists of weighing a specimen to 0.1 mg accuracy before and after treatment in the atmosphere to be tested. If the specimen is not scaled, a loss in weight represents decarburization while a gain in weight represents carburization. In order to put the results on a common basis for the comparison of one sample or atmosphere with another, the change in weight of the sample tested is expressed in grams per square centimeter of steel surface. For convenience in plotting, the change in weight per square centimeter is often multiplied by 100,000 to obtain a whole number.

The size of sample should be selected so that its weight will not be too great and thereby affect the sensitivity of a chemical balance. A specimen 1 in. in diam, ¼ in. thick or sheet stock 2 by 2 by ¼ in. is convenient. The specimen should be machined and polished to remove decarburization and to provide a smooth bright surface that will indicate the effect of the atmosphere on the brightness of the steel. The specimen should be washed in solvent and dried before weighing and reweighing. It should then be placed in the furnace in such a way that all sides are fully exposed to the atmosphere. Contact with the alloy hearth or tray should be minimized and contact with ceramic hearths should be completely avoided because such hearths may cause decarburization. It is desirable to suspend the sample in the furnace by a high-alloy wire, such as nichrome.

In the application of this method for determining the equilibrium point of an endothermic atmosphere with a dew point of +35 F at 1650 F, a group of steels of various carbon contents were exposed to the furnace atmosphere for 3 hr. Results showing the change in weight per square centimeter are plotted in Fig. 7, which shows the atmosphere in equilibrium with a steel of about 0.65% C.

In heat treating steels, the practical limit in the change in weight per square centimeter depends on the thickness and the carbon and alloy content of the part. For example, a decrease in weight of 0.0005 g per sq cm will affect a piece 0.020 in. thick of 0.70% C steel enough to give a noticeable decrease in hardness, while the same steel if 0.5 in. thick may not show a noticeable effect in maximum hardness. In the heavier section carbon diffuses from the center to the surface fast enough to maintain surface carbon content and hardness. Many tests on various types of steels have established a theoretical limit of about ±0.0002 g per sq cm change in weight. A decrease of that magnitude is too small to be detected by a microscope. Thus, on thin stock the maximum practical allowable limit is −0.0002 g per sq cm, while on heavier sections and tool steels this limit may be as much as −0.0005 g per sq cm without affecting maximum hardness or wear resistance.

Carbon Restoration During Annealing

In the mill processing of steel some decarburization always occurs. This decarburized layer on bars and coils may be eliminated by "carbon restoration", that is, carburizing simultaneously with annealing in batch or continuous furnaces. The steel must be pickled free from scale before the carbon restoration treatment.

With large charges (15 to 20 tons) in batch furnaces it is difficult to get the same degree of uniformity of carbon content and depth of penetration as with a continuous furnace. To improve uniformity, a bar charge is sometimes built up in layers with spacers between every two layers. Also, during the heating cycle the charge is heated slowly, at a rate less than 50 F per hr between about 1250 F and the carbon restoration temperature.

Carbon restoration and annealing can be done in batch-type furnaces using a controllable mixture of a substantially inert gas such as class 201 and natural gas.

As an example, in a batch furnace having a chamber capacity of about 500 cu ft, carbon restoration of 0.5 to 0.6% C steels has been carried out with an atmosphere consisting of 600 cu ft per hr of class 201 gas and 75 to 100 cu ft per hr of natural gas. The natural gas is introduced after purging is completed. The composition and dew point of the gas will vary with temperature, but at 1600 F the composition will be in the range of 2 to 4% CO, 2 to 4% CH_4 and 8 to 10% H_2 with a dew point from 0 to +10 F. The amount of natural gas added to the carrier gas can be varied in order to obtain atmospheres suitable for steels of different carbon contents. The amount of natural gas that is added to the carrier gas can also be varied during the cycle in order to compensate for the effect of temperature.

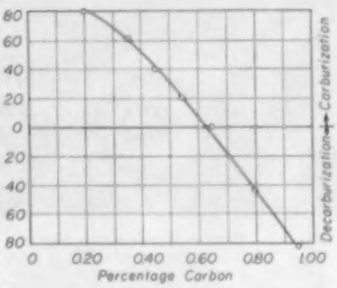

Fig. 7. Method of Plotting Changes in Weight to Show the Equilibrium Point of an Endothermic Atmosphere with a Dew Point of +35 F on Steels of Various Carbon Contents at 1650 F for 3 Hr. Shows atmosphere in equilibrium with a steel of 0.62 to 0.65% C

Carbon restoration during annealing may also be carried out by using a controllable mixture of endothermic class 302 and natural gas in continuous furnaces on bars up to 40 ft long. In such a furnace it is not economical to provide vestibules on the charge and discharge ends. To maintain proper conditions of atmosphere in the furnace the openings at the charge and discharge ends are restricted as much as possible and a large volume of inert class 201 carrier gas is provided in addition to the class 302 atmosphere. This large volume of gas escaping from the charge and discharge ends of the furnace prevents any objectionable infiltration of air into the furnace. With such a furnace, round bars may be loaded two or three deep. Bars of flat or square section will give best results with a single layer of loading.

For carbon restoration on steel of 0.5 to 0.6% C the atmosphere introduced into a continuous furnace of chamber volume 1000 cu ft consists of 5000 cu ft per hr of class 201 gas, 3600 cu ft per hr of class 302 gas, and 200 cu ft per hr of natural gas. At 1575 F the composition of this furnace atmosphere will be ap-

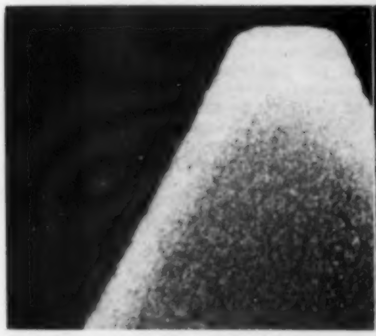

Fig. 8. Cap Screw Showing Decarburized Surface. × 45

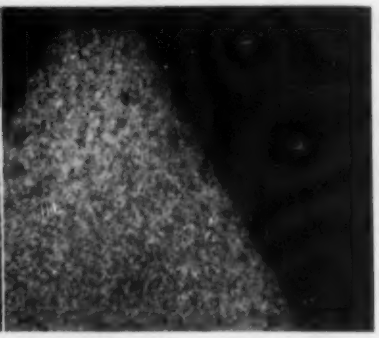

Fig. 9. Same Screw Shown in Fig. 8 After Carbon Restoration. × 45

proximately 15% CO, 0.2% CO_2, 30% H_2 and 6% CH_4. The dew point will be from about +10 to +20 F. When using a mixture of endothermic gas, prepared nitrogen gas and natural gas, the carbon potential of the furnace atmosphere can be controlled by varying the dew point of the generator gas and by varying the amount of natural gas.

Carbon restoration, simultaneous with annealing, has been carried out on steel coils in continuous furnaces. For this procedure the charge and discharge ends of the furnace are provided with vestibules to minimize air infiltration, and the coils are pushed through on trays. When they are being loaded, coils for carbon restoration should be wired loosely. This will provide maximum opportunity for the atmosphere to reach all surfaces. Especially in carbon restoration of coil that is to be used in cold heading operations, the carbon potential of the atmosphere should be controlled so as not to build up the surface carbon content to too high a level.

Carbon Restoration During Hardening

In a finished heat treated part decarburization may cause a soft surface and consequent fatigue failure. With threaded parts, thread stripping may result from decarburization. Other parts requiring high surface hardness for purposes of wear resistance are spoiled by the presence of a few thousandths of an inch of decarburization.

Surface decarburization can be eliminated by carbon restoration during the hardening treatment while austenitizing in the proper atmosphere in any type of tightly sealed furnace. A suitable atmosphere is class 302 with the desired control of carbon potential obtained by regulating the air-gas ratio to the generator. Dew points used may vary from about +5 to +70 F as shown in Fig. 1, depending on the desired carbon potential, the heat treating temperature and the steel.

Figures 8 and 9 show a cap screw before and after carbon restoration. Another example, given in Fig. 10 and 11, shows decarburized stock and successful carbon restoration at 1560 F for 2 hr followed by water quenching.

Carburizing

The control of surface carbon content in gas carburizing is dealt with in the two articles on Gas Carburizing, pages 132 to 143 of this Supplement.

Homogeneous Carburizing

Homogeneous carburizing is the carburizing of work of light cross section so that the carbon concentration is approximately the same throughout the section. For example, a thin cold formed part, fabricated from 1010 steel and then homogeneously carburized at 0.50% C, will have about the same properties after heat treatment as if it had been fabricated originally from 1050 steel.

Figure 12 shows 1010 strip fabricated into a spring shape. This same section after homogeneous carburizing for 2 hr to 0.70% is shown in Fig. 13.

Homogeneous carburizing can generally be applied to deep drawn parts and stampings that are cold formed into difficult and intricate shapes, when low-carbon steel is used so that the cold working operations can be performed satisfactorily although the final part must be of high carbon content to meet mechanical requirements. Homogeneous carburizing can also be applied to simple stampings used in lightweight mechanisms such as typewriters and business machines. Other applications are fasteners, such as spring clips and lockwashers.

Homogeneous carburizing is usually limited to parts with cross section less than ⅛ in. Beyond this thickness, there may be a fabrication problem and the heat treating cycles may be too long. Since the diffusion rates become progressively slower as the cross section approaches homogeneity, the cycles are longer than those ordinarily associated with straight carburizing.

Homogeneous carburizing can be accomplished in most commercial carburizing furnaces. Homogeneity of atmosphere and temperature is most important. Here also, availability of carbon must be considered in addition to the carbon potential of the gas, since the demand of the steel for carbon may be relatively high—especially on small parts with large surface areas.

Atmospheres for Heat Treating Tool Steels

In selecting an atmosphere that will protect the surface of tool steel against addition or depletion of carbon during heat treatment, it is desirable to choose one that requires no adjustment of composition to suit various steels. A class 501 atmosphere (ammonia base) meets this requirement and has the advantage of being sufficiently reducing to prevent oxidation of high-chromium steels. In the range of dew points generally found in this gas (−40 to −60 F) there is no serious depletion of carbon, since the decarburizing action is slow and any loss of carbon at the surface is partially replaced by diffusion from the interior. For some applications where high superficial hardness is of importance, a carburized surface can be obtained by the addition of about 1% methane to the atmosphere. Although ammonia-base atmosphere costs more than endothermic gas, this is not usually a major item of cost, since tool treating furnaces are generally small and therefore require a comparatively low flow of gas.

Endothermic-base atmosphere can be used for the protection of tool steels during heat treatment. Dew point ranges for endothermic atmospheres for hardening some common types of tool steel are given in Table II. The relatively short heating times for hardening small tools allows the treatment to be carried out with the theoretical carbon balance of the atmosphere varying over a rather wide range. However, for the hardening of large die steel sections, the particular composition of the die steel that is being treated will require careful control of the atmosphere if carburization or decarburization is to be avoided during the relatively long heat treating cycle.

Fig. 10. Round 1035 Steel Heading Bar Stock, as Received. Carbon-free depth, 0.010 to 0.012 in.; maximum affected depth, 0.015 to 0.025 in. × 100

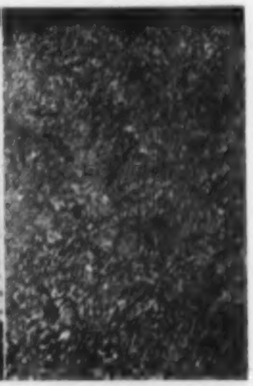

Fig 11. Same as Fig. 10 After Carbon Restoration for 2½ Hr at 1560 F. Water quenched. × 100

Table II. Range of Dew Points in Furnace Using Class 302 Endothermic Atmosphere for Hardening Some Common Types of Tool Steels(a)

AISI-SAE Type	ASM Type (1948)	Name of Steel	Furnace Temperature,(b) deg Fahr	Dew Point Range, deg Fahr Min	Max
H11,H12,H13,	IVB	Cr-W-Mo hot work die steel	1850	40	54
...	IVA2	5 Cr, 1 Mo, 1 C, air hardening	1750	40	50
S2	IIIB	Si-Mn shock-resisting chisel steel	1550	40	60
O1, O2	IIA	Mn nondeforming, oil-hardening die steel	1450	45	55
D3, D6	IIC	High-carbon high-chromium, oil hardening	1750	20	70
S1	IIID	Low-tungsten, chromium chisel steel	1750	40	45
D2, D4	IID	High-carbon high-chromium, air hardening	1850	20	70
F2, F3	VI K	Tungsten fast finishing steel	1550	23	34
W2, W3	IC	C-V shallow-hardening die steel	1500	45	55
O7	IIA3	High-carbon low-tungsten, oil hardening	1550	25	36
...	VI F	Cr-Ni-Mo tool steel	1500	50	65
T1	VC1	18-4-1 high speed tool steel	2350	0	10
M1	VA2	5-5-5 W-Cr-Mo high speed steel	2250	5	15

(a) For short times at temperature. (b) Appropriate mid-range of hardening temperature for the type

Atmospheres for Heat Treating Stainless Steels

The protective atmospheres generally used for control of surface carbon during the hardening of commonly used alloy steels may be quite unsatisfactory for stainless cutlery steels, such as types 420 and 440. Atmospheres that are reducing to ordinary steels may be oxidizing to these high-chromium steels as well as to the austenitic stainless steels and can cause the formation of a thin tenacious scale more difficult to remove than the scale produced in air. For this reason many such stainless steel parts are heated in air and the scale is removed by pickling in acid or molten salt or by blasting with iron-free sand, stainless shot or aluminum oxide. Although the hardening temperatures are high (1800 to 1900 F), as are the annealing temperatures for the austenitic steels (1950 to 2050 F), only short soaking times (10 to 15 min) are required and decarburization is therefore minimized. When scale-free heat treatment with maximum control of surface carbon is essential, an ammonia-base class 501 atmosphere is generally employed. This atmosphere is relatively inactive to carbon and has little effect at any temperature employed for the heat treatment of the cutlery grades of stainless steel. When nitrogen is objectionable because of its nitriding action on certain types of stainless steel, dried and purified hydrogen is used, but is too expensive for commercial application to stainless steels in general.

When special properties are required, such as good impact resistance with maximum resistance to wear, about 1% of methane may be added to the ammonia-base atmosphere to carburize the lower-carbon cutlery grade. Control of surface carbon concentration may be difficult, however, and a high concentration will decrease the corrosion resistance of the steel.

Atmospheres for Sintering of Iron-Carbon Parts

The sintering of iron-carbon compacts usually results in a product of approximately 0.8 to 1% C. The resulting high-carbon steel may have been shaped into such products as gears, cams, rollers or other small parts designed to resist wear. Because of the porosity of the compacts, the depth of case affected by a decarburizing atmosphere will be far greater than in wrought steel. Also, a small change in carbon content will cause a noticeable change in the dimensions of a sintered part. For these reasons any amount of decarburization in an iron-carbon sintered part is detrimental, and a closely controlled atmosphere is required in the processing of these compacts.

The sintering of iron-carbon parts is carried out principally in roller hearth or mesh-belt continuous furnaces and box-type batch furnaces. Parts are commonly loaded directly on wire mesh trays for box or roller hearth furnaces and on the belt in mesh-belt furnaces. Small parts are commonly loaded at random in a single layer. Other medium and large parts, such as gears that require the best possible dimensional control, are carefully set upright on the carriers and spaced well apart to allow uniform heating. If marking of the parts by the grid or belt becomes objectionable, auxiliary supports are used in the form of alloy sheets, either solid or perforated. Also, graphite slabs are useful supports for assuring maximum flatness of large parts.

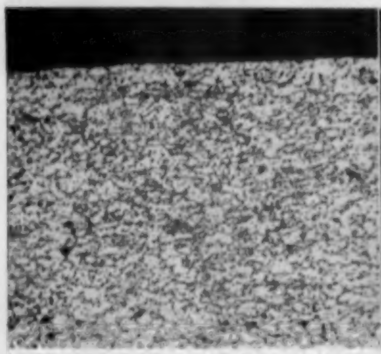

Fig. 12. Section of a Piece of Cold Rolled 1010 Strip Fabricated into a Spring Shape Before Homogeneous Carburizing

Fig. 13. Same Section After Homogeneous Carburizing for 2 Hr. at 1700 F in an Atmosphere of 0.70% Carbon Potential

The atmospheres used in sintering or subsequent annealing or hardening operations may be any of the types of high carbon potential, or of moderate carbon potential enriched with methane or propane. Endothermic class 302 is generally used with carbon potential controlled as discussed earlier.

Since the furnace atmosphere can become contaminated with either carbonaceous vapors from the binder or oxygen entrained in the voids of the compacts, a generous amount of atmosphere should be circulated through the heating chamber. This is usually accomplished by introducing the atmosphere into the furnace so that the flow in the heating chamber is counter to the progression of the work. This will keep the purest atmosphere in contact with the work at the sintering temperature, and at the same time the contaminants will be flushed out the entrance door as they are liberated from the parts being heated. The greater portion of the contaminants may be removed by having a preheat section ahead of the heating chamber. A properly vented preheat will draw off most of the carbonaceous vapors.

Atmospheres for Furnace Brazing of Steel

The need for and degree of carbon control required in the furnace brazing of steels depends largely on the temperature of the brazing operation. In the silver brazing of carbon steel parts, a relatively low temperature will be involved and no great difficulty is experienced with carbon control. Any of the suitable carbon control atmospheres may be employed. For copper brazing or other high-temperature brazing operations with carbon steels, the control is much more stringent. In this application class 302 atmospheres are generally suitable but may require hydrocarbon additions to attain the carbon potentials for high temperature.

The prepared nitrogen-base class 201 atmosphere may be suitable. This atmosphere is relatively unreactive so that it is frequently employed where low-carbon parts may be joined to higher-carbon metal in the assembly.

The ammonia-base class 501 and pure hydrogen atmospheres are employed less commonly but nevertheless quite successfully. These atmospheres do not decarburize when dry and cannot carburize any part of the assembly. However, they are not usually applied except where components of the assembly may require it, as in the copper brazing of stainless to carbon steel.

All the atmospheres mentioned in the three preceding paragraphs are of controlled carbon potential or of the reducing type. However, if it is possible or economically feasible to protect the critical surfaces with copper plating, then the only requirement of the furnace atmosphere is that it be reducing enough to prevent formation of oxides and to reduce any already present.

The Forging and Heat Treating of Tool Steel

By the ASM Committee on Heat Treating of Tool Steel

THIS ARTICLE outlines general procedures for forging and heat treating tool steel. More detailed information on the heat treatment of ten specific types of tools is given in the 1948 Metals Handbook, pages 663 to 676.

Forging must be done within the temperature range indicated in Table I, and final forging should be done on the low side of the range to refine the grain adequately. Observing the temperature of the steel during forging by use of an optical pyrometer is of great assistance in controlling the quality of the forging. The steel can be reheated as often as necessary to complete the forging, provided the above conditions are observed.

Forged tool steel products are subject to various surface irregularities, such as laps, checks, decarburization and size variations, and therefore an adequate dimensional tolerance must be provided so as to obtain the proper size after removal of the surface (see Table II, page 154).

Heating for Forging. The temperature ranges to be used are given in Table I. Heating should be slow enough to provide uniform increase in temperature throughout the steel and to allow it to go through the transformation range with a minimum of strain. The holding time at the forging temperature should be long enough to obtain uniformity of temperature and structure in the steel before forging is started. Underheating prevents adequate reduction, places an unnecessary burden on the forging equipment and results in cracked pieces (Fig. 1). Overheating may produce a coarse, brittle structure (Fig. 2), or cracking. The constituents with low melting temperatures may fuse and cause the steel to crumble. Improper heating or forging practice may cause internal bursts (Fig. 3).

The furnace atmosphere or heating medium should be adjusted to prevent decarburization, shown in Fig. 2. If this adjustment cannot be made readily, borax or a commercial preparation for the control of decarburization can be applied to the surface before heating for forging. However, borax must be used with caution because of its fluxing action on furnace hearths.

Forging Operation. Forging should start with light blows, which can be increased as the metal starts to flow. When to increase the force of the blows and when to stop and reheat are decisions at the discretion of the operator.

Cooling. Slow cooling in a furnace or an inert insulating material, such as lime or mica, is recommended to prevent possible cracking from forging stresses. This kind of cooling is not always required for carbon steels but becomes increasingly important as the alloy content increases. The air-hardening steels must be cooled slowly. It is advisable to begin the normalizing or annealing treatment before the steel cools to room temperature, but not before it has cooled to a temperature well below the transformation range.

Subdivisions

Forging 151
Normalizing 151
Annealing 151
Stress Relieving 153
Hardening 153
Quenching 154
Tempering 156

ASM-SLA F22, J, TS

ASM Committee on Heat Treating of Tool Steel

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W. H. WILLS
Metallurgical Engineer
Allegheny Ludlum Steel Corp.

Normalizing

Normalizing (Table I) requires slow and uniform heating above the transformation range to dissolve excess constituents, then cooling in still air. Normalizing breaks up nonuniform structures, relieves residual stresses, and produces greater uniformity in grain size (Fig. 4 and 5), thus counteracting undesirable results of unequal reductions for different sections during forging, differences in temperature between varying thicknesses of sections, and the subsequent irregular cooling rates. Normalizing also conditions the steel for subsequent spheroidizing, annealing or hardening. Normalizing after forging is necessary for low-alloy tool steels, unless the pieces are of a simple shape that will assure uniform forging pressures and cooling rates.

Supersedes the article on pages 653 to 655 and the table on page 657 of the 1948 ASM Metals Handbook.

Normalizing is not necessary for steel that has already been annealed by the manufacturer after forging. The more highly alloyed steels should not be normalized, because they harden appreciably when cooled in air from above the transformation range.

Annealing

Tool steel is fully annealed to relieve the stresses created by hot working, to soften the steel for machining or further processing, and to condition it for further heat treatment. If a tool is to be rehardened, it should first be thoroughly annealed. This procedure is important with the steels of higher alloy content; otherwise irregular grain growth occurs and a mixed grain size commonly referred to as "fish scale" will result. Full annealing involves heating the steel slowly and uniformly to a temperature above the transformation range, holding at temperature for 1 to 4 hr (which is generally long enough for complete penetration of the heat), and cooling slowly at a rate no greater than that shown in Table I. Controlled cooling should continue to 1100 F or lower. The annealing can be done in an electric, muffle, semimuffle, gas or oil-fired furnace, or in a liquid bath. With an oil or gas-fired furnace, the work should not be exposed directly to the flame. Decarburization and scaling can be held to a minimum by using a controlled atmosphere or properly rectified salts, or by packing in a protective material such as clean, dry cast iron chips. Controlled cooling is best accomplished in the furnace; if this is not feasible, some steels may be buried in an insulating material such as mica for slow cooling. The latter practice is not recommended for the highly alloyed tool steels such as high speed steel.

Table I gives typical hardness values of tool steels after annealing.

Isothermal (Cycle) Annealing

Isothermal annealing is best suited for applications in which full advantage can be taken of the rapid cooling to the transformation temperature, and from this temperature to room temperature. Thus, for small parts that can be handled in salt or lead baths, or for light loads in batch furnaces, isother-

Table I. Forging, Normalizing and Annealing Treatments for Principal Types of Tool Steels

Steel[a]		Forging[b]		Normalizing[c]	Annealing[d]		
AISI-SAE	ASM (1948)	Start Forging at	Do Not Forge below	Hold at Temperature, °F	Temperature, °F	Cooling Rate, °F per hr	Approx Brinell Hardness
		Temperature, °F					
Water-Hardening Tool Steels							
W1	1A	1800-1950[e]	1500	1450-1700[e]	1360-1450[e]	75	159-202
W2	IC	1800-1950	1500	1450-1700	1360-1450	75	159-202
W3	IC	1800-1950	1500	1450-1700	1360-1450	75	163-202
W4	IB	1800-1950	1500	1450-1700	1360-1450	75	159-202
W5	IB	1800-1950	1500	1450-1700	1360-1450	75	163-202
W6	...	1800-1950	1500	1450-1700	1360-1450	75	163-202
W7	...	1800-1950	1500	1450-1700	1360-1450	75	163-202
Shock-Resisting Tool Steels							
S1	IIID & IIIE	1850-2050	1600	Do not normalize	1450-1500	50	183-229
S2	IIIB	1850-2050	1600	Do not normalize	1400-1450	50	192-217
S3	....	1850-2050	1600	Do not normalize	1450-1500	50	183-212
S4	IIIC	1850-2050	1600	Do not normalize	1400-1450	50	192-229
S5	IIIC	1850-2050	1600	Do not normalize	1400-1450	50	192-229
Oil-Hardening Cold Work Tool Steels							
O1	IIA1	1800-1950	1550	1600	1400-1450	50	183-212
O2	IIA2	1800-1925	1550	1550	1375-1425	50	183-212
O6	....	1750-1900	1500	1625	1425-1475	20	183-217
O7	IIA3	1800-2000	1600	1650	1450-1500	50	192-217
Air-Hardening Medium-Alloy Cold Work Tool Steels							
A2	IIB2	1850-2000	1650	Do not normalize	1550-1600	40	202-229
A4	IIB1	1850-2000	1650	Do not normalize	1360-1400	25	200-241
A5	IIB1	1850-2000	1600	Do not normalize	1360-1400	25	228-255
A6	IIB1	1900-2050	1600	Do not normalize	1350-1375	20	217-248
High-Carbon High-Chromium Cold Work Tool Steels							
D1	IID1	1850-2000	1700	Do not normalize	1600-1650	50	207-248
D2	IID2	1850-2000	1700	Do not normalize	1600-1650	50	217-255
D3	IIC1	1850-2000	1700	Do not normalize	1600-1650	50	217-255
D4	IID3	1850-2000	1700	Do not normalize	1600-1650	50	217-255
D5	IID2	1850-2000	1700	Do not normalize	1600-1650	50	223-255
D6	IIC1	1850-2000	1700	Do not normalize	1600-1650	50	217-255
Chromium Hot Work Tool Steels							
H11	IVB	1950-2100	1650	Do not normalize	1550-1650	50	192-229
H12	IVB	1950-2100	1650	Do not normalize	1550-1650	50	192-229
H13	IVB	1950-2100	1650	Do not normalize	1550-1650	50	192-229
H14	IVC	1950-2150	1700	Do not normalize	1600-1650	50	207-235
H15	IVE1	1900-2100	1650	Do not normalize	1550-1600	50	207-229
H16	IVD	1950-2150	1700	Do not normalize	1600-1650	50	212-241
Tungsten Hot Work Tool Steels							
H20	IVF1	1950-2150	1650	Do not normalize	1600-1650	50	207-235
H21	IVF1	1950-2150	1650	Do not normalize	1600-1650	50	207-235
H23	IVF2	1950-2150	1650	Do not normalize	1600-1650	50	207-235
H22	....	1950-2150	1800	Do not normalize	1600-1650	50	213-255
H24	IVF3	1950-2150	1750	Do not normalize	1600-1650	50	217-241
H25	IVF3	1950-2150	1700	Do not normalize	1600-1650	50	207-235
H26	IVF4	1950-2150	1750	Do not normalize	1600-1650	50	217-241
Molybdenum Hot Work Tool Steels							
H41	....	1900-2050	1700	Do not normalize	1500-1600	50	207-235
H42	....	1900-2050	1700	Do not normalize	1550-1650	50	207-235
H43	....	1900-2050	1700	Do not normalize	1500-1600	50	207-235
Tungsten High Speed Tool Steels							
T1	VC1	1950-2150	1750	Do not normalize	1600-1650	50	217-255
T2	VC2	1950-2150	1750	Do not normalize	1600-1650	50	223-255
T3	VC3	1950-2150	1750	Do not normalize	1600-1650	50	229-269
T4	VD2	1950-2150	1750	Do not normalize	1600-1650	50	228-269
T5	VD3	1950-2150	1800	Do not normalize	1600-1650	50	235-275
T6	VD4	1950-2150	1800	Do not normalize	1600-1650	50	248-293
T7	....	1950-2150	1750	Do not normalize	1600-1650	50	217-255
T8	VD1	1950-2150	1750	Do not normalize	1600-1650	50	228-255
T9	....	1950-2150	1800	Do not normalize	1600-1650	50	235-277
T15	....	1950-2150	1800	Do not normalize	1600-1650	50	241-277
Molybdenum High Speed Tool Steels							
M1	VA2	1900-2100	1700	Do not normalize	1500-1600	50	207-235
M2	VA3	1900-2100	1700	Do not normalize	1600-1650	50	212-241
M3	....	1900-2100	1700	Do not normalize	1600-1650	50	223-255
M4	VA4	1900-2100	1700	Do not normalize	1600-1650	50	223-255
M6	....	1900-2100	1700	Do not normalize	1600	50	248-277
M7	....	1900-2100	1700	Do not normalize	1500-1600	50	217-255
M8	....	1900-2100	1700	Do not normalize	1550-1600	25-30	217-241
M10	VA1	1900-2100	1700	Do not normalize	1500-1600	50	207-235
M15	....	1900-2100	1700	Do not normalize	1600-1650	50	241-277
M30	VB1	1900-2100	1700	Do not normalize	1600-1650	50	235-269
M34	VB2	1900-2100	1700	Do not normalize	1600-1650	50	235-269
M35	VB3	1900-2100	1700	Do not normalize	1600-1650	50	235-269
M36	VB4	1900-2100	1700	Do not normalize	1600-1650	50	235-269
Low-Alloy Special Purpose Tool Steels							
L1	....	1800-2000	1550	1650	1425-1475	50	179-207
L2	IIIA	1800-2000	1550	1600-1650	1400-1450	(f)	163-196
L3	VIJ	1800-2000	1550	1650	1450-1500	50	174-201
L4	....	1800-2000	1550	1650	1425-1475	50	179-207
L5	....	1800-2000	1550	1650	1425-1475	50	183-223
L6	VIF1 & E	1800-2000	1550	1600	1400-1450	50	183-212
L7	....	1800-2000	1550	1650	1450-1500	50	183-212
Carbon-Tungsten Tool Steels							
F1	....	1800-2000	1550	1650	1400-1475	50	183-207
F2	VIK	1800-2000	1650	1650	1450-1500	50	207-235
F3	VIK	1800-2000	1650	1650	1450-1500	50	212-248
Low-Carbon Mold Steels							
P1	VIA	(g)	(h)	Not required	1350-1650	50	81-100
P2	....	1850-2050	1550	Not required	1350-1500	50	103-123
P3	VIB	1850-2050	1550	Not required	1350-1500	(f)	109-137
P4	....	1850-2050	1600	Do not normalize	1600-1650	25	116-128
P5	....	1850-2050	1550	Not required	1550-1600	40	105-110
P6	....	1950-2150	1700	Not required	1550	30	207
P20	....	1850-2050	1600	1650	1400-1450	50	150-180

(Continued on the next page)

mal annealing makes possible large savings in time, as compared with the conventional slow furnace cooling. It can also be adapted conveniently to continuous annealing cycles where adequate equipment is available.

Generally, isothermal or cycle annealing consists of austenitizing at a temperature usually not higher than 100 F above the Ac_1 temperature, and cooling rapidly to a temperature usually not more than 100 F below the Ac_1 temperature. The steel is held at this lower temperature until transformation to the annealed product is complete, and is then cooled to room temperature in air. There is no metallurgical reason for slow cooling during the change from the austenitizing to the transformation temperature, or after transformation is completed.

The austenitizing temperatures for full annealing, listed in Table I, can be used as an approximate guide for isothermal annealing. Time-temperature transformation charts for particular steels may be consulted for more specific information. The time at the austenitizing temperature is generally 2 hr. The transformation times and temperatures are usually 2 to 6 hr at 1275 to 1300 F for the W, S and L steels, and 4 to 6 hr at 1400 to 1450 F for the A, D, H, T and M steels.

Isothermal annealing offers no particular advantage for applications such as the batch annealing of large furnace loads in which the rate of cooling at the center of the load may be so slow as to preclude any rapid cooling to the transformation temperature. For such applications, conventional full annealing usually offers a better assurance of obtaining the desired properties.

Stress Relieving

Stress relieving removes residual stresses induced in tools by heavy machining or other cold working. The elimination or reduction of these stresses decreases the probability of cracking and excessive distortion during hardening of the tool. The usual range for such stress relieving is from 1100 to 1300 F. Protection against scaling or decarburization usually is not required. Cooling should be slow enough to avoid introducing new stresses. The higher the temperature (below the transformation range), the greater the stress relief. The amount of stress relief obtained by this procedure is usually sufficient; for complete relief the steel must be fully annealed.

After stress relieving, it may be necessary to correct certain dimensions before hardening, since relief of stresses causes some dimensional change. Precision tools are usually stress relieved after machining and before hardening but it is often desirable to rough machine, then stress relieve before finish machining.

The ground surface of a hardened tool may be highly stressed after grinding but not cracked. These high stresses may develop cracks immediately after grinding, before use or during use. Tools in such condition can often be salvaged by stress relieving, immediately after grinding, at or just below the tempering temperature in order to maintain the specified tool hardness.

Tools also develop high residual stress in use. It is sometimes advantageous to relieve such stresses at each redressing of the tool by retempering at the proper temperature for the tool in question. The temperature for such stress relief should never exceed the tempering temperature; otherwise, undesirable softening will occur.

Hardening

The purpose of hardening is to develop a serviceable combination of hardness, toughness and wear resistance. The treatment consists of heating the steel to a temperature above the transformation range, holding at that temperature to obtain solution of carbides, and then cooling rapidly in water, oil, or some other quenching medium, depending on the type of steel used. Quenching is followed by tempering, as discussed below. The recommended hardening ranges and quenching mediums for the various types of tool steel are given in Table III. The hardening of specific tools is described on pages 663 to 675 of the 1948 Metals Handbook; the heat treatment of gages on page 31 of the 1954 Supplement; tools for hot extrusion on page 26, and tools for cold drawing on page 27.

Equipment used for hardening tool steels includes direct-fired and semi-muffle oil and gas furnaces, gas and electric furnaces with controlled atmosphere, and liquid baths. Liquid baths are best suited for a large volume of work and continuous operation; controlled atmosphere furnaces heat more slowly and are more economical for

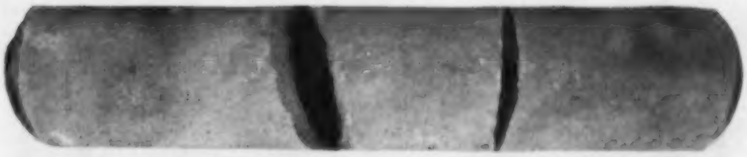

Fig. 1. Cracks Resulting from Underheating During Forging

Table I. Forging, Normalizing and Annealing Treatments for Principal Types of Tool Steels (Cont.)

Steel[a] AISI-SAE	Steel[a] ASM (1948)	Forging[b] Start Forging at Temperature, °F	Forging[b] Do Not Forge below Temperature, °F	Normalizing[c] Hold at Temperature, °F	Annealing[d] Temperature, °F	Annealing[d] Cooling Rate, °F per hr	Annealing[d] Approx Brinell Hardness
Other Steels Listed in 1948 Metals Handbook and Not Included Above							
..	IVA1	1800-2000	1650	Do not normalize	1475-1525	50	187-217
..	IVA2	1800-2000	1650	Do not normalize	1475-1525	50	187-217
..	VIC	1900-2100	1550	Not required	1350-1500	(f)	131-170
..	VID	1950-2150	1600	Do not normalize	1550-1600	(f)	170-207
..	VIF2	1900-2100	1550	1600	1400-1450	(f)	179-207
..	VIF3	1900-2100	1550	1600	1400-1450	(f)	183-212
..	VIG	1900-2100	1550	1650	1425-1475	(f)	183-212
..	VIH	1800-2000	1550	1650	1425-1475	50	174-201
..	VI-I	1800-2000	1550	1650	1450-1500	50	174-201

(a) The compositions of these principal types of tool steels are listed on page 22 of the 1954 Supplement.

(b) The temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions. As the alloy content of the steel increases, the time of soaking at forging temperature increases proportionately. Likewise, as the alloy content increases, it becomes more necessary to cool slowly from the forging temperature. With very high-alloy steels, such as high speed steels and air-hardening steels, this slow cooling is imperative in order to prevent cracking and to leave the steel in a semisoft condition. Either furnace cooling or burying in an insulating medium such as lime, mica, or silocel, is satisfactory.

(c) The length of time the steel is held, after being uniformly heated through at the normalizing temperature, varies from about 15 minutes for a small section to about one hour for large sizes. Cooling from the normalizing temperature is done in still air. The purpose of normalizing after forging is to refine the grain structure and to produce a uniform structure throughout the forging. Normalizing should not be confused with low-temperature (about 1200 F) annealing used for the relief of residual stresses resulting from heavy machining, bending and forming.

(d) The annealing temperature is given as a range, the upper limit of which should be used for large sections and the lower limit for smaller sections. The length of time the steel is held, after being uniformly heated through at the annealing temperature, varies from about one hour for light sections and small furnace charges of carbon or low-alloy tool steel, to about 4 hr for heavy sections and large furnace charges of high-alloy steel.

(e) Forging, normalizing and annealing temperatures of water-hardening tool steels are given as ranges because they vary with carbon content. The following temperatures are recommended:

Forging
  0.60 to 1.25% C: the range given
  1.25 to 1.40% C: the low side of the range
Normalizing
  0.60 to 0.75% C: 1500 F
  0.75 to 0.90% C: 1450 F
  0.90 to 1.10% C: 1600 F
  1.10 to 1.40% C: 1600 to 1800 F
Annealing
  0.60 to 0.90% C: 1360 to 1400 F
  0.90 to 1.40% C: 1400 to 1450 F

(f) Slowly in furnace

(g) Forging should be done between 2200 and 2350 or 1450 and 1550 F; the steel should not be worked between 1600 and 1900 F.

(h) Should not be forged below 1900 or 1450 F (see note g).

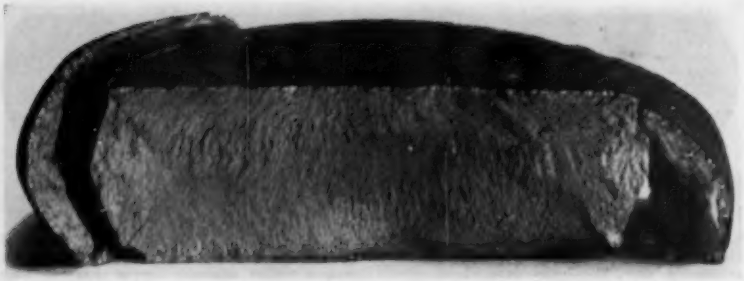

Fig. 2. Excessive Decarburization and Coarse Grain from Overheating during Forging

small production and intermittent operation. Tools have been heated for hardening by induction, especially where differential hardening is necessary or a large number of similar tools of a suitable size and shape are involved. For complete details on fuel-fired furnaces see pages 267 to 272 of the Metals Handbook, pages 273 to 280 for information on electric furnaces, pages 283 to 291 for salt baths, and pages 107 to 123 (this Supplement) for induction heating.

Heating for Hardening. The rate of heating for alloy tool steels should be slower than for plain carbon steels and should decrease as the alloy content increases. Slow, uniform heating reduces warpage. Heating for hardening is most rapid in molten baths and by induction, slower in open or semi-muffle fuel-heated furnaces, and slowest in electric or muffle furnaces. Rate of heat transfer is also affected by the type of furnace atmosphere and the circulation of atmosphere.

Since dimensional changes occur in steel during heating, some stress is produced in the tool, depending on its size and shape. To avoid sudden changes in temperature and to reduce thermal shock, large or intricately shaped tools should be charged in a furnace operating at low temperature, preferably below 1200 F. After their temperature has been equalized with that of the furnace, the tools can be heated to the hardening temperature.

Preheating in a separate furnace at 1000 to 1300 F, then transferring to another furnace held at the hardening temperature is common for tool steels that are hardened from temperatures below 2000 F. This reduces the time required in the hardening furnace and avoids excessive stresses, scaling and decarburization. High speed steels and others that are quenched from above 2000 F should be preheated at 1400 to 1600 F, depending on the type, before transfer to the hardening furnace.

Holding at Temperature. To achieve uniform heating may require manipulation of the tool during heating. Because steels are soft at or above their hardening temperature, tools should be supported properly with suitable fixtures above the furnace hearth to avoid sagging and to reduce the tendency to warp. Long, slender tools should be supported vertically when practicable.

A range of temperature is given in the recommendations for hardening temperature (Table III); however, this does not mean that satisfactory results can always be obtained if the tool is held anywhere within that range. Generally, small or intricately shaped tools are heated to the low side of the range and larger sizes to the high side. The best hardening temperature is the one that produces the best combination of as-quenched hardness and grain refinement. The tool should be held at temperature long enough to attain uniform temperature throughout the section and proper solution of the carbides, so as to produce the desired hardness, structure and grain size.

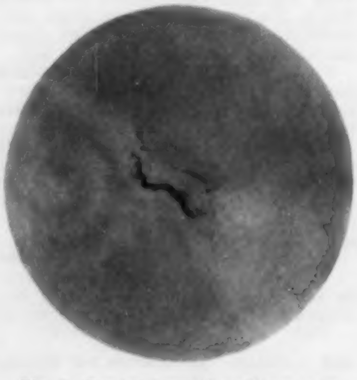

Fig. 3. Center Burst Resulting from Improper Forging Practice

Excessive time at or above the hardening temperature may cause grain coarsening and, under certain conditions, surface decarburization, carburization, or cracking (Fig. 6). This increases the hazard of cracking in quenching and may impair the resistance of the tool to repeated stresses in service. Underheating may result in low hardness with lower wear resistance. At the time of quenching, if the center of the tool is cooler than the exterior, spalling or fracturing of the corners may result (Fig. 7), particularly with water-hardening steels.

Atmospheres and Salt Baths

In producing tools that will give maximum service life, it is essential to control the furnace atmosphere or the liquid heating medium surrounding the tool during heating for hardening, to avoid detrimental decarburization, carburization and scaling.

The selection of the furnace atmosphere or the liquid heating medium depends on the chemical composition of the tool steel and on the hardening temperature. For carbon tool steel (W), oil-hardening steel (O), and other types hardened below 1600 F, a slightly oxidizing or neutral condition gives best results. For hot work steel (H), a neutral condition gives best results. For air-hardening steel (A), high-carbon high-chromium steel (D), and high speed steel (M and T) that are hardened above 1600 F, a reducing or neutral condition gives best results.

For further information the reader may refer to the following five articles:

1. Salt Baths, page 283, 1948 Metals Handbook
2. Lead Baths, page 291, 1948 Metals Handbook
3. Protective Furnace Atmospheres, page 294, 1948 Metals Handbook
4. High Speed Steel Cutting Tools, page 665, 1948 Metals Handbook
5. Control of Surface Carbon Content in the Heat Treatment of Steel, page 144, this Supplement

Pack Hardening. If controlled-atmosphere furnaces or liquid baths are not available and it is necessary to protect the surface, pack hardening may be used. The tools are packed in a container with cast iron chips, spent carburizing compound, pitch coke or other neutral material, which should be dry and free from dirt or scale. The entire charge is sealed, brought up to the hardening temperature, and when the tools are heated through, they are quickly removed and quenched.

The possibility of carburization or decarburization from packing material must be considered. Carburization may cause cracking during quenching, grinding sensitivity or later failure by cracking in service. Decarburization or carburization by pack hardening can be completely avoided by first copper plating the tool to be pack hardened. Since copper melts at 1981 F, its use to protect against carburization or decarburization is limited to steels that can be hardened from below this temperature. Advantages of pack hardening result from the relatively slow rate of heating, which promotes good uniformity of temperature, and from good support of delicate and intricate tools so that distortion is minimized.

Table II. Tolerances and Machining Allowances for Hot Finished Tool Steel Forgings

Diameter or Distance Across Flats,(a) in.	Allowance for Machining, in.	Additional Tolerance Over Allowance,(b) in.
3 or less	1/8	1/8
3 to 5	3/16	3/16
5 to 7	5/16	5/16
7 to 12	3/8	3/8
12 to 18	1/2	1/2
18 to 24	5/8	5/8
24 to 32	3/4	3/4

(a) Width and thickness tolerances are in accordance with the dimensions given in first column, the inside and outside diameters take their own respective tolerances. (b) All values are plus as given, minus zero.

Pyrometers. Adequate pyrometer equipment is essential to good heat treating results. The modern indicating or recording pyrometer is a precision instrument that should have the best of care and should be checked regularly. For accurate measurement of temperature the thermocouple should be placed on the tool or as close as possible to it.

Base-metal couples have short service life at temperatures above 2000 F, but they can be replaced frequently at small cost. Platinum thermocouples and optical pyrometers are more commonly used for temperatures above 2000 F. Often both an indicator and a recorder are used in automatic control systems, with one providing verification of the other. (For more information on pyrometers and thermocouples see the article on page 174 of the 1948 Metals Handbook.)

Quenching. Selection of the quenching medium is determined by the speed of cooling necessary to harden a steel. This factor is affected by the composition and hardenability of the steel (Table III). The most common quenching mediums are water, brine, oil, air and molten baths. The volume of coolant should be sufficient to maintain the quenching medium at the proper temperature for uniform results.

Water. The water should be at a fairly constant temperature, from 60 to 80 F. Warm water is less satisfactory because it vaporizes faster and prevents effective removal of heat. Aerated water may produce soft spots. Sprays or geysers are a great help in obtaining uniform hardness by eliminating gas pockets and washing away scale that may be present. Ring or cold header dies are commonly quenched with a spigot or quick-acting valve and special fixtures. If still water is used, tools should be quenched with short, brisk up-and-down movements so as to cool them rapidly through the transformation range. Best results are obtained if the tools are removed from the bath while still warm (slightly below 200 F).

Brine. Tools are quenched more effectively in 5 to 10% sodium chloride brine than in water, especially when still or mildly agitated baths are used. Brine has less tendency to form steam on contact with hot steel and less tendency to absorb and release atmospheric gases. Tools quenched in brine will throw their scale more readily, producing a cleaner surface of more uniform hardness. Brine should be at a fairly constant temperature, from 60 to 80 F.

Submerged sprays or geysers should be used for tools having considerable mass or intricate shape requiring a directed flow of quenchant. Cooling efficiency of the brine is not increased by increasing salt concentration to more than 10%. In fact, the quenching speed is reduced as salt concentration approaches a saturated solution (26%).

Tools quenched in brine should be rinsed in water to decrease susceptibility to corrosion. They should be removed from the bath when their temperature is approximately 150 to 200 F and should be tempered without delay. An alternative is to place the tools in a bath at 150 to 200 F until tempering is possible.

Because of the steep thermal gradient between surface and center of large sections during the quenching operation, such sections should be equalized at 150 to 200 F before the tempering treatment.

Oil. Because the removal of heat is slower than in water or brine, quenching in oil causes less warpage and lower residual stresses in the steel. Best results are obtained from an oil quench at 100 to 150 F, or sometimes at higher temperatures as a precaution against cracking. Cold quenching oil may produce variable hardness or cracking because of its high viscosity. A satisfactory quenching oil is reasonably stable, does not react chemically with the hot steel, has a high flash point, and the same quenching speed over a wide range of temperature. Oils of various quenching speeds are available. For further information, the reader may refer to the section on liquids for deep hardening steels, page 618, 1948 Metals Handbook.

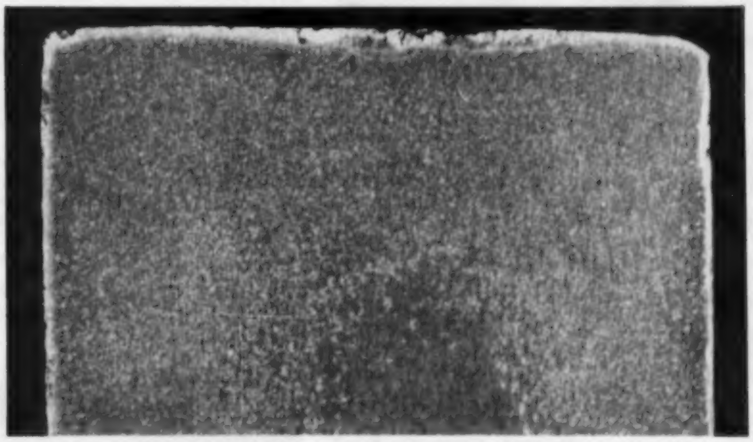

Fig. 4. Nonuniform Structure before Normalizing

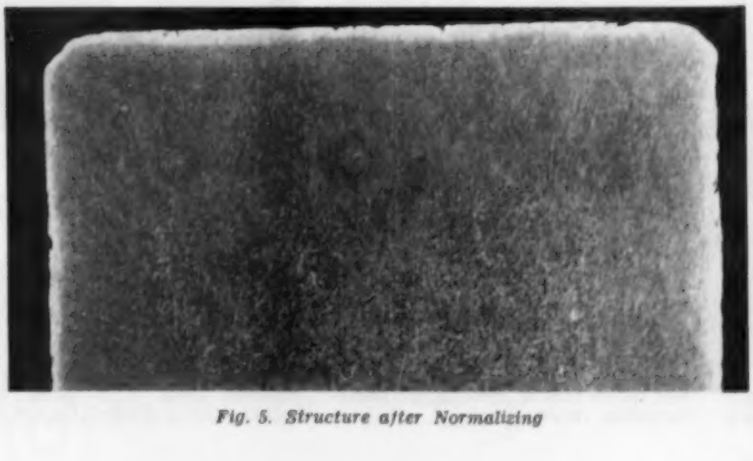

Fig. 5. Structure after Normalizing

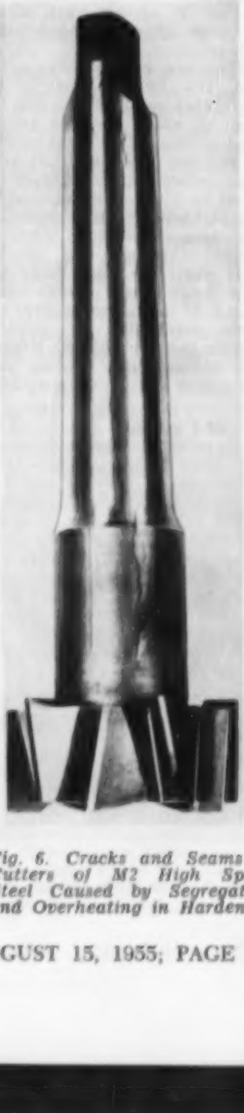

Fig. 6. Cracks and Seams in Cutters of M2 High Speed Steel Caused by Segregation and Overheating in Hardening

Table III. Comparison of Principal Groups of Tool Steels

Steel Group[a]							
AISI-SAE	ASM (1946)	Distortion in Hardening	Safety in Hardening	Quenching Medium	Hardening Temperature Range,[b] deg Fahr	Depth of Hardening	Tendency Toward Decarburization
W	I	High	Low-Med	Water	1400 to 1600	Shallow	Low
O	IIA	Medium	Medium	Oil	1400 to 1600	Medium	Low
A	IIB	Low	High	Air	1450 to 1850	Deep	Medium
D	IIC, IID	Low	High	Air, Oil	1700 to 2000	Deep	Medium
H	IV	Low	High	Air, Oil	1700 to 2250	Deep	Medium
T	VC, VD	Low	High	Oil, Air, Salt	2150 to 2400	Deep	Medium
M	VA, VB	Low	High	Oil, Air, Salt	2125 to 2275	Deep	High
S	III	Med-High	Low-Med	Water, Oil	1550 to 1800	Medium	High

(a) Steels in groups F, P and L are omitted from this table because they represent specialized applications.

(b) The purpose of this column is to show the broad ranges of temperature employed in hardening. This information may serve to indicate the heat treating equipment required; it is not to be used as a specification. For more exact information, see the articles on heat treatment of tool steels, pages 660 to 676 of the 1948 Metals Handbook.

Oil baths should be checked frequently for the presence of water, which is undesirable as it may cause cracking. Excessive amounts of scale and sludge on the bottom should be avoided. Compressed air should not be used for agitation. Tools hardened in a salt bath should be quenched in a straight mineral oil, which will not be decomposed by the salt on the tools.

Air. Cooling in air is preferred for hardening certain types of highly alloyed tool steels, including the air-hardening die steels (A and D), and sometimes for hot work steels (H) and high speed steels (M and T). These tool steels may be air cooled in any of several ways: (1) still air, which is atmospheric air undistributed by artificial circulation; (2) air discharged from a fan; or (3) an air blast, which is the discharge of compressed air from a high-pressure line.

When any of the three methods are used, the tool should be supported (preferably on a screen off the floor) so as to allow uniform access of air to all surfaces. If a blast of compressed air is used, the air must contain no water, which can readily cause cracking of an air-hardening steel.

Straightening. In general, water-hardening steels warp more than oil-hardening steels, and air-hardening steels warp the least. Long thin tools warp more than short heavy ones. Causes of excessive warpage may be heavy machining or cold working stresses, poor tool design, improper support or improper heating conditions, and wrong quenching practice.

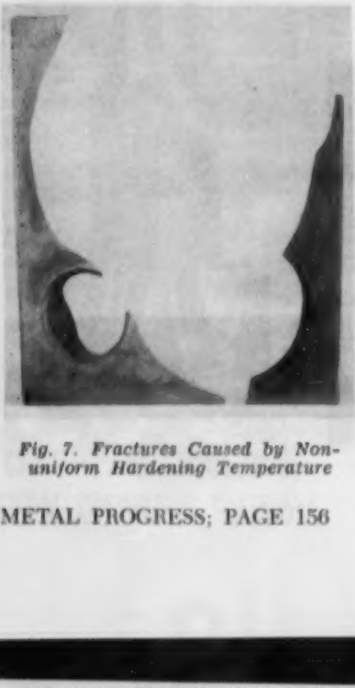

Fig. 7. Fractures Caused by Nonuniform Hardening Temperature

Tools may be straightened by peening or bending in a vise or suitable press, or by rolling between plates of suitable thickness. When straightening is required, it should be done during cooling from the hardening temperature. For water-hardening and oil-hardening steels, the tools should be withdrawn from the quenching bath at about 500 to 600 F, and straightening may be continued to just above the M_s point (about 400 F for most types). Air-hardening or high speed steels may be straightened at any time during cooling, preferably before they reach 400 F.

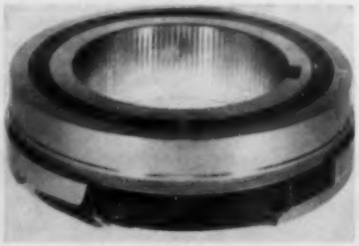

Fig. 8. Cracking Induced by Tempering Too Late after Quenching

Interrupted Quenching. High speed and other highly alloyed steels frequently are given an "interrupted" quench in oil, salt or lead, to about 1000 F, and then cooled in still air to a temperature at which the steel can be handled with the bare hands. By air cooling below 1000 F, cooling stresses are reduced, which minimizes distortion. During the air cooling cycle, the tool may be straightened with small likelihood of breakage until a temperature of 400 F is reached.

If the temperature of the steel, when removed from the quenching medium, is just above the temperature at which martensite begins to form during cooling (400 to 600 F) the method is called "marquenching", a procedure that generally minimizes distortion and cracking in irregularly shaped parts of medium or highly alloyed steels. The cooling rates obtainable in the molten baths for marquenching restrict this quenching method to steels that can be hardened in oil or air with conventional quenching. Advantages of interrupted quenching are that it decreases (1) warpage, (2) possibility of cracking during quenching, (3) surface oxidation and (4) temperature differential between the surface and center of the tool before cooling through the transformation range.

Tempering

Quenched tools are often in a highly and nonuniformly stressed condition. The stresses are relieved by heating the hardened tool to a temperature well below the transformation range and then cooling slowly to room temperature. This tempering treatment also "toughens" the steel. Since the danger of cracking is most pronounced just after quenching, the tools should be tempered as soon as they can be handled comfortably with bare hands. Figures 8 and 9 show failures caused by delaying tempering after quenching.

Rate of Heating. Heating to the tempering temperature should be slow to obtain uniform distribution of temperature within the tool and to prevent the nonuniform relief of hardening stresses that could cause cracking or warping. Satisfactory results may be obtained by charging the tools into a freely circulating medium at the desired tempering temperature and then permitting them to reach this temperature. Various mediums may be used for tempering. If liquid is employed, the tools should be placed in a basket and not permitted to come in contact with the hot walls or bottom of the pot or tank. Heat transfer is most rapid for molten lead baths, less for salt and oil baths, and slowest in still air.

Enough time should be allowed during tempering for the temperature to be distributed uniformly through the tools before time at temperature is counted, especially at low tempering temperatures and with tools that have large sections. Table IV indicates the time needed for various section sizes to reach temperature completely in different kinds of furnaces. If not enough time is allowed for the tool to

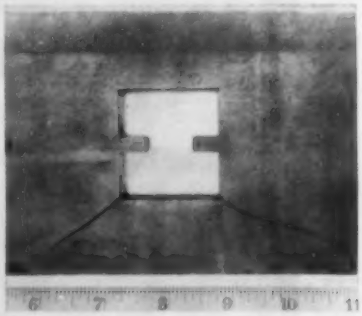

Fig. 9. Cracks Caused by Delay in Tempering after Quenching

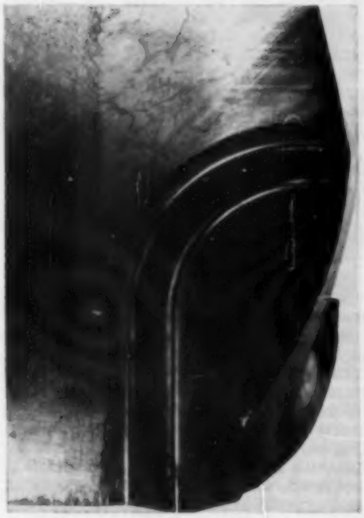

Fig. 10. Grinding Cracks Caused by Absence of Stress Relief

reach the tempering temperature, the result will be unequal tempering and possible damage to the tool. Color of the oxide film should not be used as a guide in tempering, because these temper colors merely indicate the surface temperature of the tool and not the internal temperature. Tendency for grinding cracks in hardened tools may sometimes be traced to inadequate tempering (Fig. 10 and 11).

Time at Temperature. With certain exceptions for highly alloyed tool steels, the lower the tempering temperature, the longer the tool must be tempered to effect the desired results. Specific time-temperature recommendations for particular steels and tools are given in the pertinent articles in the 1948 Metals Handbook and the 1954 Supplement.

Multiple Tempering is more effective than a single tempering operation for highly alloyed steels. Double or triple tempering is often advisable for air-hardening (A and D), hot work (H), and high speed steels (T and M). The first treatment tempers the martensite formed during quenching and conditions the retained austenite for transformation to martensite during cooling to room temperature from the tempering temperature. The second treatment is then necessary to temper the martensite formed during the first tempering operation. The third tempering, when used, further decreases the amount of untempered martensite still remaining.

Cooling after tempering should be relatively slow in order to prevent residual stresses in the steel. Still air is generally a satisfactory medium.

Cold Treatment. The purpose of cold treatment is to increase the transformation of retained austenite to martensite. The usual practice is to cool the tool, after tempering, to a subzero temperature in the range from —90 to 120 F, and then retemper it. Tool steels such as high-carbon high-chromium (D) and high speed (M and T), which have a considerable amount of retained austenite after quenching, may benefit from cold treatment. Cold treatment will not correct the coarse grain structures (which may impair toughness) caused by overheating during hardening. Cold treatment used in conjunction with multiple tempering is effective for stabilizing the dimensions of gages.

A Nitride Case will often increase tool life and can be applied to any type of high speed steel (M and T). This treatment produces a surface hardness substantially greater than obtained by the usual hardening procedure. Such a case is produced by heating the finished tool in a cyanide bath at 1050 F for 15 min to 2 hr. Time at temperature depends on the depth of case desired. The usual time is about 30 min. An important factor before nitriding is a fine finish on the cutting edges and faces of the tool subject to chip wear. The treatment also results in additional tempering and the relief of detrimental surface stresses set up during finishing.

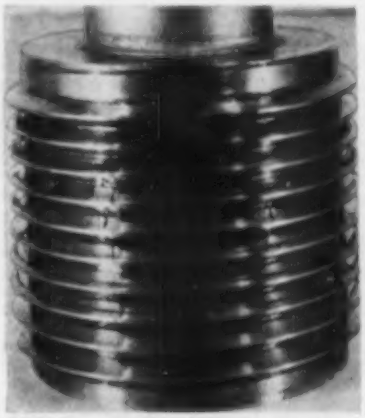

Fig. 11. Grinding Cracks Caused by Omission of Tempering

Hard Chromium Plating is particularly helpful on cutting tools such as taps and reamers that may clog with chips or where the chips may weld to the cutting edges. A fine finish before plating is important. Plate thickness of 0.0001 to 0.001 in. is usually sufficient. After plating, the tools should be stress relieved at 300 to 400 F to prevent hydrogen embrittlement.

Oxide Coating produces a thin (approximately 0.0001-in.) coating of black iron oxide (Fe_3O_4) that adheres tenaciously to a steel surface. When applied to finished high speed steel tools, the coating aids in holding lubricants and resisting chip pickup and wear. The treatment also results in additional tempering and relief of surface stresses formed during finishing of the tools.

The oxide coating is applied to tools that have been properly hardened, tempered and ground. The process consists of heating the finished tools in a recirculating type of furnace at 950 to 1050 F using a steam atmosphere and sufficient time to produce the desired depth of oxide followed by cooling in air.

Table IV. Approximate Heating Time to Attain Tempering Temperature
(Must not be used as tempering time)

Tempering Temperature, deg Fahr	Time Required to Reach Furnace Temperature,[a] min per in.					
	In a Hot Air Oven, Without Circulation[b]			In a Circulating Air Oven or an Oil Bath[c]		
	Cubes or Spheres	Squares or Cylinders	Average Flats	Cubes or Spheres	Squares or Cylinders	Average Flats
250	30	55	80	15	20	30
300	30	50	75	15	20	30
350	30	50	70	15	20	30
400	25	45	65	15	20	30
500	25	40	60	15	20	30
600	25	40	55	15	20	30
700	20	35	50	15	20	30
800	20	30	45	15	20	30
900	20	30	40	15	20	30

(a) Data are per inch of diameter or thickness, with furnace maintained at the temperature indicated in column 1. For temperatures above 900 F, use times quoted for 900 F. Data may be used as a guide for charges of irregular shapes and quantities by estimating total size of charge and applying the above allowance to the number of inches from outside to center of charge.

(b) Figures apply to a dark or scaled surface on the tool. If the tool surface is finish ground, or otherwise brightened, twice as much time should be allowed in a still hot-air oven. No extra allowance need be made for bright surfaces in a circulating oven, or in an oil bath.

(c) An oil bath can be used only at the lower temperatures.

Metals Handbook Articles on Heat Treatment of Tool Steels

The 1948 Metals Handbook describes, in separate articles, the heat treatment of three major classes of tool steel:

Carbon tool steel
"Nondeforming" tool steel
Shock-resisting tool steel.

The remainder of the 1948 section on tool steels consists of ten articles on the heat treatment of specific tools:

High speed steel cutting tools
Die blocks and hot die inserts
Hot forging machine tools
Hot and cold trimming tools
Solid shear blades
Press tools for cold shearing, blanking, punching, forming and coining
Cold heading dies
Thread-rolling dies
Die-casting dies and permanent molds
Plastic molds.

Heat treating information was included in the 1954 Supplement for the following items: gages (page 31), tools for hot extrusion (page 26), and tools for cold drawing (page 27) — none of which were in the 1948 Handbook.

Selection of Electrodes for Manual Arc Welding of Low-Carbon Steel

By the ASM Committee on Selection of Welding Electrodes

Subdivisions

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ASM-SLA K1, CN

SELECTION of the proper electrodes for manual arc welding of low-carbon steel depends on the quality required in the welded assembly, the equipment available, the weld location, cost, base metal, joint design and desired weld properties. The influence of each of these factors and their interrelations as they affect production welding are described in this article.

The ten principal types of electrodes commonly used are listed in Table I by their AWS-ASTM designations. The classification is on the basis of tensile strength of the deposited weld metal, type of covering, type of current, and welding positions of the electrodes. Any electrode included under one classification is not included under another. The prefix "E" designates *electric* arc welding electrodes. The first two digits indicate tensile strength of deposited weld metal; for example, E60xx means 60,000 psi tensile strength (not stress relieved). The third digit indicates position of the work: Exx1x indicates all positions; Exx2x indicates horizontal fillets or flat position; Exx3x indicates flat position only. The fourth digit cannot be considered individually; the third and fourth digits together indicate polarity. There are no requirements for chemical composition of either the wire or weld metal.

Several of these electrodes are called "all-purpose" because they will make a satisfactory weld in all welding positions. The engineer's problem is to determine which one of the many available should be used. For example, an E6010 electrode is an all-purpose electrode but will not operate on alternating current or give the soundness of deposit that is often required in the welded assembly.

An E6012 electrode is an all-purpose electrode that will operate on both alternating and direct current, but will not produce a weld having the ductility or penetrating qualities of E6010. The low-hydrogen E6016 is another all-purpose electrode; welds made with it have excellent strength, ductility and impact resistance, and it will weld high-sulfur steel. However, its cost is relatively high, it is susceptible to moisture pickup with resulting high porosity and, in the vertical and overhead positions, is generally used in smaller diameters than the E6010 or E6013.

Many electrode classification charts have been published showing the basic characteristics or differences in electrodes, such as type of current to be used, positions in which to be used, type of coating, tensile strength and relative ductility (the latter often derived from tests that are in no way related to the eventual use of the electrode). Because such charts are often misleading — since they do not list any of the many variables encountered in production that determine the acceptability of an electrode — most fabricators conduct their own tests to decide which electrode is best suited for a particular application.

Selection Factors

Most of the important variables that influence electrode selection are listed with a relative rating in Table II. Since ten classifications of electrodes are listed, the highest rating has been taken as 10 and the lowest as 1. Six of the ten electrodes are not recommended for certain specific factors.

Table II can be used in many ways. Often only a few variables, or perhaps only one, determine the selection. For example, if high-sulfur steel is to be welded, factor 8 indicates that either the E6016 or E60xx electrode should be used. If the selection is to be made on the basis of overcoming a poor fit-up, factor 16 in the table indicates that E6012X and E6012 are best for such a condition. The X in E6012X designates a variation of the E6012 electrode. E6012X electrodes are made primarily for use in high-speed welding of thin sheet involving poorly fitted joints and the requirement of shallow penetration of the weld metal.

More frequently the problem is to make a selection from several electrodes that are listed in Table II as being satisfactory. The problem can be lessened by determining which of the variables are of greatest consequence to the selection; then, by comparing these with the recommendations given in Table II, the selection can be narrowed considerably.

Supplements the article on page 371 of the 1948 ASM Metals Handbook

For example, in a specific selection problem the factors of primary importance might be as follows: butt welding to be done in all positions; equipment available for the job employs alternating current; steel to be welded is heavy plate; a high rate of weld deposition is required; welded joints will be inspected radiographically for soundness; and the weld metal must have the highest possible ductility and resistance to impact at low temperatures. Comparing these requirements with the variable factors in Table II, it is found that these correspond to the items numbered 2, 5, 7, 9, 12, 13 and 14.

Referring to the table and factor 2, it is found that electrodes E6020, E6024 and E6027 are not recommended for all-position welding and thus are eliminated. Factor 5 states that E6010 is not recommended for use with alternating-current welding equipment; according to factor 7, E6012X is not recommended for welding of heavy plate. Thus, the selection possibilities have been reduced from ten electrodes to five.

The choice now can be narrowed still further by adding up the assigned values of the pertinent factors for each of the remaining five electrodes and selecting the electrode having the highest value. The values for the E6011 electrode for factors 2, 5, 7, 9 12, 13 and 14 total to 43 points, E6012 to a total of 29, E6013 to 38, E6016 to 52 and E60xx to 51. The low-hydrogen E6016 and E60xx electrodes have the highest value and would be selected, unless the welders are not trained to use the more costly electrodes or other factors beyond the scope of the tables make the selection undesirable. Then the choice would be between E6011 and E6013, again on the basis of greatest importance to the particular job or of other factors that did not originally come into consideration. For example, if low-temperature impact strength, factor 14, is of greatest importance, E6011 would be selected. However, if deposition rate, factor 10, is of greatest importance, E6013 would be selected.

Weld and Position. The first four factors in Table II refer to the configuration and position of the weld. These factors are most important in determining over-all cost of the welding operation and in the preliminary selection of the electrode.

The flat position is best because it allows the highest rate of welding. For joints that require weld metal to be deposited in fillets or grooves, the electrodes of high deposition rate, E6024, E6027, E6020 and E60xx, are best in that order. High deposition rates with radiographic quality are obtainable in heavy plate. The flat or concave bead, which washes up the side of the groove or fillet, insures clean multiple-pass welds.

When root sealer beads are necessary in butt welds, E6011 with alternating current or E6010 with direct current can be used. They are capable of producing welds of radiographic quality and have a thin, easily removable slag as well as a rapid rate of solidification.

The all-purpose E6012 and E6013 are used for all-position welding. Although they are not ideally suited for flat work, they have good operating characteristics. In multiple-pass fillet or groove welds, the convex bead of the E6012 electrode leaves corners that are difficult to clean and remelt. It is not suitable for radiographic quality, but is suitable for poor fit-ups since it has a viscous puddle that readily bridges gaps. The E6013 electrode has a flat bead and an easily removable slag, so it can be used to better advantage in multiple-pass work than E6012. The advantage of E6013 is its easy operating characteristics in all positions, but in the flat down position deposition rate and penetration are inferior to E6020.

The recently introduced iron powder electrodes E6024 and E6027 are used for flat welds and the iron powder E60xx for flat and all-position welding. These three electrodes are easy to operate, have very high deposition rates, virtually no spatter, and with most brands of E6024 the arc can be struck on the coating. However, they cost more than the other commercial electrodes. Their application is not well established yet, although the weld deposit from E6024 is stronger than that from conventional counterpart electrodes.

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Table I. Electrodes Commonly Used for Welding Low-Carbon Steel

AWS-ASTM Electrode Class	Coating	Current[a]	Welding Positions[b]	Electrode Cost	Volume Used, %
E 6010......	High-cellulose, sodium	DCR	F, V, OH, H	100	23.4
E 6011......	High-cellulose, potassium	DCR, AC	F, V, OH, H	108	6.6
E 6012......	High-titania, sodium	DCS, AC	F, V, OH, H	100	30.4
E 6012X	High-titania, sodium special	DCS, AC	F, H	100	(c)
E 6013......	High-titania, potassium	DCS, AC	F, V, OH, H	104	10.7
E 6016......	Low-hydrogen, potassium	DCR, AC	F, V, OH, H	120	5.3
E 60xx[d]...	Low-hydrogen, iron powder	DCR, AC	F, H	182	(c)
E 6020......	High-iron oxide	DCR, DCS, AC	F, H	100	6.6
E 6024......	Iron powder, titania	DCR, DCS, AC	F, H	154	(c)
E 6027......	Iron powder, iron oxide	DCR, DCS, AC	F, H	147	(c)

(a) DCR—direct current reverse, electrode positive; DCS—direct current straight, electrode negative; AC—alternating current. (b) F—flat; V—vertical; OH—overhead; H—horizontal. (c) Not available. (d) AWS-ASTM class number not yet assigned.

Types of Joint. The square-groove butt shown in Fig. 1 is a simple economical joint usable on plates up to a maximum of ⅜ in. thick when welded from both sides. Thinner sections can be welded from one side by using a backup strip. This type of joint requires a "digging" arc to get good penetration but a high burn-off rate is not necessary because little filler metal is required. E6011 (ac) or E6010 (dc, reverse polarity) is most satisfactory for this application. The cutting action of the arc and the light slag often eliminate the necessity for back-chipping before welding the second pass. Where poor fit-up is encountered, a filler bead can be deposited from the same electrodes. Butt welds on joints with root openings up to 3/16 in. can be made with electrodes of lower penetration rating. If 100% fusion and penetration are required, the root opening should be used and the second side welded should be back-chipped to the metal that is free from defects.

V-groove joints, shown in Fig. 2, are used when the plate is too thick for square-groove joints. They are also used for steel of composition outside the range for best welding, since it is not necessary to melt as much base metal into the bead. For best economy, an electrode having the highest rate of deposition should be used.

Where single V-joints can be welded from one side only, a root sealer bead must be laid to fill in the gap. E6010 or E6011 may be used for easy removal of slag or an E6016 electrode for welds of better quality. The fluid puddle from the E6020 electrode will drop through if a sealer bead is not used. However, when a backup strip is used with a V-joint, no sealer bead is necessary. For best economy all passes can be made with electrodes of high deposition rate. General-purpose electrodes E6012 and E6013 also are used for groove butt welds, but E6013 is generally preferred. It produces a flatter bead, a sounder deposit and its slag is more easily removed.

The double V-groove, shown in Fig. 3, is used because of heavy plate thickness or to minimize distortion. A sealer bead, which is needed to close the center gap, requires an electrode that produces a quickly solidifying bead with thin slag, easily removable; E6010, E6011 and E6016 are best for this purpose. For maximum economy, a high

Table II. Relative Ratings of Factors Affecting Preliminary Selection of Electrodes[a]

	Variable Factors	Electrode Class									
		E6010	E6011	E6012	E6012X	E6013	E6016	E60xx	E6020	E6024	E6027
1	Groove butt welds, flat (> ¼ in.)...................	4	5	3	2	8	7	9	10	9	10
2	Groove butt welds, all positions (>¼ in.)...........	10	9	5	4	8	7	6	(b)	(b)	(b)
3	Fillet welds, flat or horizontal......................	2	3	8	7	7	5	7	10	10	7
4	Fillet welds, all positions..........................	10	9	6	4	7	8	6	(b)	(b)	(b)
5	Current[c]	DCR	AC DCR	AC DCS	AC DCS	AC DC	AC DCR	AC DC	AC DC	AC DC	AC DC
6	Thin material (<¼ in.)............................	5	7	8	10	9	2	2	(b)	7	(b)
7	Heavy plate or highly restrained joint.............	8	8	6	(b)	8	10	9	8	7	8
8	High-sulfur or off-analysis steel....................	(b)	(b)	5	4	3	10	9	(b)	8	(b)
9	Deposition rate	5	5	7	7	7	5	8	9	10	10
10	Depth of penetration................................	10	9	6	5	5	7	7	8	4	8
11	Appearance, undercutting	6	6	8	7	9	7	10	9	10	10
12	Soundness	6	6	3	3	5	10	8	9	8	9
13	Ductility	6	7	4	3	5	10	10	10	5	10
14	Low-temperature impact strength...................	8	8	4	4	5	10	10	8	9	9
15	Low spatter loss..	1	2	6	6	7	6	8	9	10	10
16	Poor fit-up	6	7	10	10	8	4	4	(b)	8	(b)
17	Welder appeal	7	6	8	8	9	6	8	9	10	10
18	Slag removal	10	8	6	6	8	4	7	8	8	8

(a) Rating (for same size electrodes) is on a comparative basis for electrodes listed in this table; 10 is highest value. Ratings may change with change in size. (b) Not recommended. (c) DCR—direct current reverse, electrode positive; DCS—direct current straight, electrode negative; AC—alternating current; DC—direct current, either polarity deposition rate is needed to fill the groove. Quality might require a slower deposition rate.

Other types of joints used for heavy plate include the J, U, and double-U joints shown in Fig. 4. The double-V joint can be prepared by all cutting processes, whereas the J and U normally must be machined. The double-V is preferred to avoid machining costs.

A flat fillet weld is shown in Fig. 5. A flat bead and easy slag removal are desirable for multiple-pass welds. Electrodes of high deposition rate (E6020 and E6027) produce welds of best quality. When fit-up is poor, electrodes of high deposition rate should not be used because of the fluidity of the molten pool. E6012 is best where irregularities are to be bridged, and it is also used for short, intermittent, single-pass welds.

The E6013 electrode produces fillet welds of good quality, even though its deposition rate is lower than that of some other electrodes. It is easy to operate and is usually readily available.

The flat-position, open-joint corner weld, shown in Fig. 6, requires an electrode with a viscous puddle that will not drop through and a viscous slag that will not run over. E6012, E6013 or E6024 electrodes should be used to obtain best results.

A lap weld and a horizontal fillet weld are shown in Fig. 7. Whenever these can be made in the flat position the E6020, E6024, E6027 or E60xx electrodes normally are used. If these welds must be made in the horizontal position, the E6012, E6020, E6024 or E60xx electrodes are used. For other out-of-position welds, either the E6010, E6011, E6012, E6013 or E6016 electrodes are used, as indicated in Table II.

Current. Factor 5 deals with the characteristics of the current to be used. If deep penetration is desired, direct current with the electrode positive is the best choice. If high deposit rates and low penetration are desired, direct current with the electrode negative is the best choice. If a good deposition rate and freedom from arc blow are desired, alternating current should be used. Alternating current does not provide the same stability of arc as direct current but is quite satisfactory for most jobs.

Thickness. Factors 6 and 7 could be divided on the basis of limitations of thickness. As used in the table, factor 6 pertains to carbon steel less than ¼ in. thick; factor 7, to metal of all greater thicknesses. The E6010, E6012 and E6013 electrodes constitute about 80% of the electrodes used. For thicknesses greater than ⅜ in., E6012 and E6013 electrodes are used because of their good deposition rates and the general soundness of the deposits. For steel plate 1⅛ in. thick or more, low-hydrogen electrodes generally are selected because of their superior resistance to cracking and excellent ductility and impact strength.

High-Sulfur Steel. Factor 8 is of great importance whenever the sulfur content of the steel is on the high side. Low-hydrogen electrodes are the best choice for welding such steel. The coatings on these electrodes produce a slag that combines with the sulfur to form a basic sulfide rather than allowing the sulfur to combine with the steel and form iron sulfides, which may cause high porosity or cracking. The low-hydrogen electrodes are also the first choice for welding off-analysis steels or those with carbon on the high side. Because of the absence of hydrogen, the higher-carbon steels can be welded with fewer cracking problems.

Deposition Rate is a very important factor, since it governs the cost of labor required to produce a given weld. Factor 9 could be divided into deposition rates for various current sources, different positions and atmospheric conditions. In Table II the values of deposition rates are on an average basis, with the flat-position electrodes E6020, E6024 and E6027 showing a superiority.

The deposition rate and efficiency are determined by measuring the weight of weld metal deposited from a given weight of electrode in a selected unit of time. This necessarily takes into account the stub-end loss, the spatter loss and the coating loss. Maximum deposition rate can be secured with each electrode at some specific current value above which the rate will fall because of additional stub-end loss, spatter loss and loss due to vaporization of the metal. In the vertical, horizontal and overhead positions, a limiting current is reached beyond which the weld metal will no longer stay in place satisfactorily during deposition.

Penetration. Factor 10 in Table II lists the relative values of penetration for each electrode. The E6010 and E6011 electrodes, with values of 10 and 9 respectively, provide the most penetration. E6020 and E6027 are the next best. By deep penetration is meant the ability of the weld metal to penetrate deeply into the parent metal with subsequent high dilution. An example of its value is in making deeply penetrated fillet welds so an adequate throat depth can be secured without depositing an excessive amount of metal.

Another example is the use of such an electrode in a single-V butt joint, such as a circumferential pipe joint, in which the first pass digs deep into the root and virtually deposits a pass of weld metal on the back side.

Appearance. The appearance of a weld consists of many factors such as smoothness of surface, weld contour, freedom from undercut, merging with the surface and well-merged starting and stopping points. A sufficiently smooth bead can be deposited from the flat position with E6012, E6013, E6020 and iron powder electrodes to make grinding unnecessary before radiography. The appearance of welds, particularly those made in the vertical, horizontal or overhead welding position, is very important; so is contour.

Soundness of a weld, as evaluated by factor 12 in Table II, is the average of subfactors such as porosity, cracks, slag, inclusions, microfissures and other defects. Lack of soundness promotes poor ductility, low impact strength, low tensile strength and costly repairs. Not all defects in a weld can be detected by radiography. Small first-pass cracks, microfissures and some types of nonfusion must be found by mechanical testing or by metallographic examination. Preheat treatments improve the soundness of welds by eliminating cracks and microfissures.

Ductility, listed as factor 13 in Table II, is a measure of the ability of a weldment to deform without failing and is particularly important in weldments containing high angular and lateral restraint. Since the contraction accompanying the cooling of a weld is opposed by the surrounding metal (see page 89 of the article "Residual Stresses" in this Supplement), the weld metal must flow plastically under conditions of severe restraint in order to satisfy the shrinkage requirement.

A weld that is 1 in. wide or long will shrink in both directions 0.0000065 in. per in. per deg Fahr. For a temperature change of 2000 deg, the weld will shrink 2000 x 0.0000065 in., or 0.013 in. If completely restrained, the weld must flow plastically this amount — or crack. Preheat treatments reduce the amount of this restraint by decreasing the temperature range through which the weld must cool. Postheat treatment is also beneficial in tempering brittle phases that may have been produced, particularly for heavy sections. Such treatments are also often dictated by code requirements and experience gained in fabrication.

Low-Temperature Impact Strength of a weld, factor 14, is unimportant unless the weldment is to be used at subzero temperature. Structures being built today under existing code rules can withstand service conditions of

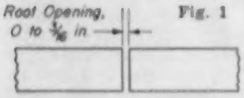


Fig. 1

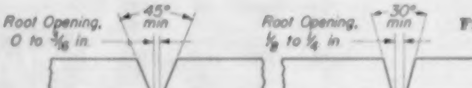


Fig. 2

Fig. 3

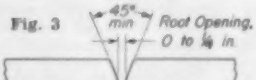


Fig. 4

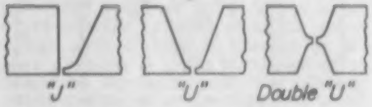


Fig. 5

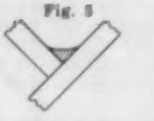


Fig. 6

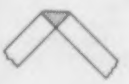


Fig. 7

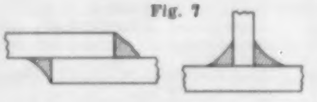


Fig. 1. Butt Weld, Square Groove. Fig. 2. Butt Weld, Single-V Groove. Fig. 3. Butt Weld, Double-V Groove. Fig. 4. Butt Weld, J, U and Double-U Grooves. Fig. 5. Flat Fillet Weld. Fig. 6. Flat-Position, Open-Joint Corner Weld. Fig. 7. Lap Weld and Horizontal Fillet Weld

—50 F, although special steels and electrodes are required. Plain carbon steels do not perform satisfactorily below —50 F; the weld metal often has mechanical properties superior to those of the base metal. Typical values for low-temperature impact strength of weld metal are included in Table III.

Spatter Loss, factor 15 in Table II, might easily have been included in factor 9 for deposition rate. However, on certain applications spatter presents a specific problem in cleaning, painting or enameling. An antispatter compound can be used to minimize this difficulty, but it is preferable to select electrodes that have low spatter.

Poor Fit-Up, factor 16, has been a problem to everyone using welding. Fast-setting electrodes help correct this difficulty and improve the efficiency of deposition. The ideal solution, of course, is to avoid poor fit-up. Since this cannot always be done, the next best solution is to use an electrode that will do the most satisfactory job under such conditions. Because the resulting weld may not be of greatest ductility and soundness, the importance of this factor must be evaluated.

Welder Appeal, factor 17, often works against the quality of a weld. As an example, the E6016 electrode requires a more exacting technique and may appeal less to the welder. However, the resulting weld may have properties that outweigh the welder's dislike for the electrode. Certain characteristics of an arc have welder appeal, such as smoothness, quietness, and freedom from slag in the puddle. A very stable arc, easy to strike and hold is another. An electrode that requires a minimum of manipulation also makes the welder's work easier.

Slag Removal, factor 18, is important in both cost and quality of the weldment. If slag is too difficult to remove, it may be entrapped in the weld as a result of imperfect cleaning. The cost of cleaning is proportional to the time required to remove slag, and an easily removed slag generally leaves a weld of better appearance.

* * *

After a type of electrode has been selected it is advisable to make tests to verify that the factors used for the selection actually represent the problem.

Size of Electrode

Although no exact rules can be stated, the following may be useful as a guide in selecting the proper size of electrode:

1 For pipe welds (or single-welded joints) requiring good fusion at the root, 1/8 or 5/32-in. diam electrode is recommended for the first pass. The remainder of the joint may be made with 5/32 or 3/16-in. diam electrode for all positions and 3/16-in. diam or larger if the electrode is used in flat positions only.
2 For flat welding of double-beveled or single-beveled joints that have a back-up strip or can be back-chipped, a 3/16-in. electrode may be used for the first pass and 7/32-in. or larger for the remainder.
3 For fillet welds in the flat position, either 3/16, 7/32 or 1/4-in. electrodes are satisfactory. Larger electrodes may be used if the work is thick enough to take care of the additional heat.
4 For out-of-position work, both butts and fillets, a 3/16-in. electrode is the maximum size warranted. Often the first pass is deposited with a 5/32-in. electrode. The sizes of low-hydrogen electrodes for vertical and overhead welding generally are 1/8 and 5/32 in., and for flat and horizontal positions the sizes are 3/16 in. and larger.
5 For welding of sheet steel and light-gage work, see discussion under Welding Thin Sections, page 162.

Effect of Steel Composition

To obtain the highest welding speeds, high currents and burn-off rates are required. The high burn-off rates may result in extensive alloying of the plate or base metal with the weld metal. If a considerable amount of the plate metal becomes a part of the weld, the chemical composition of the plate becomes an important consideration.

The limits of composition of carbon steel given in Table IV are those conducive to maximum speed of welding. The specification limit for sulfur in these low-carbon steels is ordinarily 0.05% but sulfur contents below 0.045% are usual. When steels outside the limits of the preferred composition range are used, having more than one element toward the high limit, corrective measures may be necessary in the welding procedure.

The preferred composition range has been chosen so that virtually no restriction need be made as to the type of joint, type of electrode, welding current or speed of welding. That is, such steel allows the user to take full advantage of large electrodes, high currents, high speeds, and techniques for obtaining deep penetration. Usually steels within this range are available without premium price and can be fabricated easily by the usual forming, shearing, machining and other mechanical processes.

If welding costs far outweigh machining costs on a particular job, it may be wise to change from a free-machining steel to a more easily weldable steel at some sacrifice in machinability. Or, service may require a steel of higher yield strength or greater resistance to corrosion, without regard to its poor weldability and increased welding costs.

Steels suspected of poor welding quality should be test-welded to determine whether cracking or porosity is likely. If the steel welds readily in such tests, standard welding procedures can be used, usually at less than maximum speed. If cracking occurs, one or more of the following precautions should improve the soundness of welds:

1 Produce flat or slightly convex beads; a concave bead is more likely to crack than flat or convex beads. That is, avoid the types of electrodes, such as E6020, that usually produce the concave type of bead.
2 Melt as little as possible of the off-analysis parent metal into the weld deposit. (a) Use electrodes of low penetration, preferably E6012 or E6024, which make a convex bead. If E6010 or E6011 electrodes must be used because of out-of-position work, a low-penetration technique plus some preheating will usually be necessary. (b) Decrease current or increase arc length slightly to reduce penetration. Use V-joints if necessary, to obtain the required weld section.
3 Put in as large a weld as feasible in the first pass, especially on thick plates, by using slower speed of travel. This increases the weld section to give better resistance to the stresses resulting from contraction, which might crack a weld of smaller section. Slow speed also increases the heat input for a given length of weld, thereby decreasing the rate of cooling and the hardening of the weld zone. The second pass should be applied while the plate is still warm from the first pass.
4 Leave a gap between plates to allow for free movement while the weld contracts during cooling.
5 Weld toward the unrestrained end of a joint. Make tacks that do not restrain the joint excessively.
6 If E6012 or E6024 electrodes do not eliminate the weld cracking, or if the cracks are in the parent metal adjacent to the weld, E6016 or E60xx low-hydrogen electrodes should be tried. These prevent underbead cracking caused by hydrogen embrittlement. They also will usually eliminate cracking in the weld deposit because of their low-penetrating arc, good bead shape, and the high quality of the weld metal obtained.
7 If cracking occurs even with the E6016 or E60xx electrodes, preheating may be required, to retard the cooling and prevent excessive hardening in the weld and the metal adjacent to it. (For welds made with conventional mild steel electrodes, the preheating temperature usually is between 250 and 600 F. If low-hydrogen electrodes are used, a temperature of 300 F or less is sufficient.) If cracks appear in the crater only, the backstepping method

Table III. Typical Mechanical Properties of Deposited Weld Metal

Electrode Class	Tensile Strength, psi	Yield Strength, psi	Elongation in 2-In., %	Charpy V-Notch Impact, ft-lb Room Temp	Charpy V-Notch Impact, ft-lb Low Temp
E 6010	65,000	53,000	24	70	18 (—40 F)
E 6011	65,000	53,000	25	70	18 (—40 F)
E 6012	72,000	64,000	19	50	18 (0 F)
E 6012X	72,000	64,000	19	50	18 (0 F)
E 6013	72,000	64,000	19	60	15 (—40 F)
E 6016	72,000	62,000	28	95	40 (—40 F)
E 60xx	77,000	65,000	30	95	40 (—40 F)
E 6020	64,000	53,000	28	70	18 (—40 F)
E 6024	85,000	72,000	10	60	20 (—40 F)
E 6027	69,000	50,000	28	70	20 (—40 F)

ASTM A233-55T procedure

Table IV. Limits of Carbon Steel Composition for Best Welding Conditions

Element	Composition, % Low	Composition, % Preferred	Composition, % High
Carbon	0.10	0.13 to 0.20	0.30
Manganese	0.30	0.40 to 0.60	0.90
Silicon	...	0.10 to 0.15	0.30(max)
Sulfur	...	0.035(max)	0.05(max)
Phosphorus	...	0.04 (max)	0.04(max)
Residual elements (Cr, Ni, Mo, Cu)	...	0.10 (max)	0.25(max)

should be used so that the weld is finished on top of the bead previously deposited. The crater will then penetrate into weld metal instead of plate metal, and the concentration of undesirable elements may be low enough to prevent cracking.

8 If preheating is not practicable, it may be advisable to use a nonhardenable austenitic electrode such as 25 Cr – 12 Ni; 25 Cr – 20 Ni; or 18 Cr – 8 Ni – Mn, modified. Coatings on these are of the low-hydrogen type, and the electrodes produce ductile, tough weld deposits that do not harden with sudden cooling.

Surface holes caused by too high a content of sulfur, silicon or carbon usually can be eliminated by employing one of the following expedients: increasing the arc length, using a less penetrating electrode, decreasing the current, or using low-hydrogen electrodes.

Some factors responsible for internal porosity are high sulfur, too low or too high combined carbon and manganese content of the parent metal, and high moisture in the coatings of some types of electrodes or welding joints or both. The use of low-hydrogen electrodes such as E6016 or E60xx according to recommended procedure may be the corrective measure.

Welding Thin Sections

Thin sections of the base metal are defined arbitrarily as those less than ¼ in. thick. Electrodes generally used are E6011, E6012X and E6013. E6011 may be used where good penetration is necessary, but should not be used on sheet less than about 0.060 in. thick. E6013 may be used for welding sheet as thin as about 0.050 in. and will give a smoother weld bead than will the electrode E6011.

With the thinner sheets several factors besides electrode composition influence quality of the weldment. For a given welding current, less trouble from burning holes and excessive penetration will be experienced with a larger electrode. Under the same conditions of current and speed of travel, a typical ⅛-in. electrode caused 17 holes to be burned through 0.036-in. sheet in a weld length of approximately 60 in. The same brand in 5/32-in. size, at the same current and travel speed, did not burn holes through the sheet.

"Drag technique" should be used whenever possible to minimize the need for operator's skill and to increase welding speeds. This technique is not confined to the electrodes having high contents of metal powder in the coating. At high current, with drag technique, there has been no observable difference in the performance of the electrodes whether used with alternating or direct current. Both work satisfactorily.

Figure 8 shows some typical joints on thin metals welded in various positions at average speeds. In general, the recommended fit-up for such joints is a gap of 1/16 in. or less for thicknesses greater than about 0.100 in. if deep penetration is required, and no gaps for thinner material or where shallow penetration is desired.

For the welding of a thin sheet to a thick section, electrode selection and other variables are determined on the basis of the thickness of the thin sheet. For example, if 0.062-in. sheet is to be welded to 0.50-in. plate, an E6013 would be satisfactory. The best fit-up for a fillet weld would have no gap. The average speed for flat welding would be 14 in. per min; for vertical down, 18 in. per min; and for welding in the overhead position, 12 in. per min.

Appearance

Poor appearance of welds is usually caused by incorrect procedure for a given parent metal or incorrect choice of electrode. The most common defects are weld spatter, undercuts, cracks and porosity.

Weld Spatter is an appearance defect generally of no consequence to the structural function of the weld. Excessive spatter is unnecessary, however, and its appearance on a weldment is not pleasing. It may be caused by one or more of the following factors: unnecessarily high welding current, wrong electrode, wrong polarity, too long an arc length, or welding too close to the ground terminal with d-c electrodes (arc blow).

Undercut, unless it is extreme, is also more of an appearance defect than a structural detriment. It is usually considered undesirable and to be avoided if possible. It may be caused by too high a welding current, excessive speed, improper electrode manipulation, or attempting to use an electrode in a position for which it was not designed. A uniform weave of the electrode helps to prevent undercutting during welding of V-butt joints.

Excessive weaving motion of the electrode will cause undercutting and should be avoided. On welds in vertical plate with a horizontal fillet, undercutting may be caused by the electrode being too far from the plate.

Cracking should not be a problem in the welding of low-carbon steels, especially when the steel is less than ½ in. thick. Any cracks are considered a weld failure, or at least the beginning of a condition that may lead to weld failure. The most common cracks in and near a weld joint are crater cracks, underbead cracks and longitudinal cracks. There also may be hairline cracks across the weld and microcracks in the weld metal. While these various cracks appear in different parts of the weld and result from different causes, in general, they can all be eliminated in the steels considered in this article.

Cracking may be caused by one or more of the following irregularities:

1 Inadequate weldability of the base steel because of composition outside specification limits
2 Improper preparation of the joints
3 Wrong welding procedure
4 Excessive rigidity of the joint
5 Welds too small for the size of the parts being joined in the structure

Often cracks can be avoided if the open ends of the weldment are allowed to move and rigid joints are avoided. A gap of 1/32 in. should be allowed for thick plates. Crater cracks may be eliminated by carefully filling the weld crater at the end of each weld.

Porosity in welds is undesirable even though it may not decrease strength. Surface holes in the weld bead have an undesirable appearance and can result in cracks and other defective weld conditions. One of the major causes of porosity is off-analysis steel. Dirt, rust and paint in a joint may also cause porosity. At the start of a weld made with low-hydrogen electrodes, porosity may be the result of too much moisture in the electrode coating or weld area, the use of a welding current too low or an arc too long. Porosity at the finish end of a weld may be caused by a breakdown of the electrode coating as a result of the current being too high.

Welding procedure has a strong effect on the soundness of welds. Excessive currents should be avoided. Each layer of weld metal must be completely free from slag and flux before another layer is deposited. Puddling will allow the entrapped gases to escape. Low-hydrogen electrodes must be stored in a dry place to prevent the coating from picking up excessive moisture from the atmosphere. Reducing current to the correct value will help to prevent excessive breakdown of the electrode coating. One of the purposes of the coating is to produce a protective atmosphere around the arc; the coating cannot do so if it deteriorates.

Electrode Coatings

The chemical composition of the covering of each class of welding electrode largely determines the performance of the electrode and the quality of the weld metal deposit. Table V lists the basic materials in electrode coverings that are designed to meet the AWS-

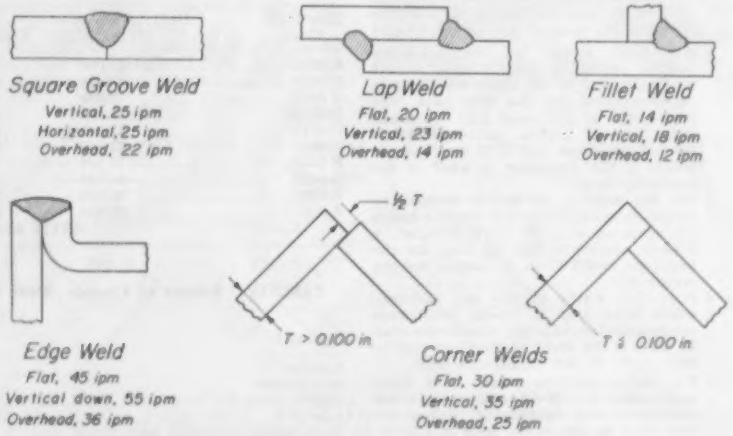


Fig. 8. Average Welding Speed for Various Types of Thin Metal Joints

ASTM requirements for each type of electrode represented. Other constituents are added with these to meet commercial requirements.

Between 30 and 40% of the covering of E6010 is cellulose. During welding, the cellulose is converted to CO, CO_2, H_2 and other gases that form a protective shield for the arc. The decomposition of the cellulose leaves a low volume of slag that is usually easy to remove. The large amount of water vapor evolved from the decomposed cellulose gives this electrode a concentrated, deeply penetrating arc, which makes the electrode suitable for welding on galvanized plate and on dirty, heavily scaled plate.

The combination of materials in the coating causes the weld deposit to freeze rapidly during welding, which makes these electrodes excellent for out-of-position work. Also, the covering materials, when properly proportioned, sometimes give deposits with good mechanical and radiographic properties. Sodium silicate used in combination with the other materials in the E6010 covering makes the electrode usable only for direct-current, reverse-polarity welding.

The E6011 electrodes are E6010's with alternating-current welding characteristics incorporated in their design. The potassium in the potassium silicate has a low ionization potential to help maintain an arc through the points of almost zero energy in the alternating-current cycle. Except for this difference, the behavior of the coatings is similar to E6010.

The E6012 electrodes are suitable for all welding positions with both alternating current and direct current, straight polarity. Table V lists a group of materials that could be used to make a satisfactory E6012 electrode. The fact that the coating has either no cellulose or a very small amount, and a rather large amount of refractory materials such as rutile and mineral silicates, accounts for the general ability of this type of electrode to operate at high current. Through the use of higher currents, welding speeds can be increased and consequently higher production rates often can be realized. The combination of materials in the coverings of E6012 electrodes is responsible for keeping the weld metal viscous. Therefore, these electrodes perform well where there is poor fit-up. The viscous weld metal will run very slowly, if at all, through an opening in a joint and will solidify before it can progress very far.

The E6013 electrodes are similar to the E6012's. The earlier E6012's were not designed for welding with alternating current. E6013's were introduced as E6012's for alternating-current use, especially in small diameters. Sodium silicate was used as a binder in the earlier E6012 electrodes. Better welding characteristics with alternating current were incorporated in the E6013 through the use of potassium silicate as a binder.

Many E6012 electrodes have potassium compounds in their coatings and consequently have good welding characteristics with alternating current. In fact, electrodes are available that fall between the original E6012 and E6013 types with regard to composition of coating; therefore it is difficult to classify them definitely as either an E6012 or E6013 type.

The E6012X electrode is a specially designed E6012 for high-speed application to light gage metal using a drag technique. It has a coating composition similar to the standard E6012, modified to take higher current with shallow penetration and greater fluidity of both slag and weld metal. The greater fluidity permits weld metal to fill in behind the arc better at high speeds.

In general, E6013 electrodes have a higher cellulose content than E6012 and so lack the ability of E6012 to withstand high amperage. Also E6013 has a "softer" and more globular type of arc than E6012 and consequently is more suitable for welding thin metal. The combination of higher cellulose content and potassium silicate binder results in better mechanical properties.

There is no cellulose in the coating of the E6016 electrodes, and the use of hydrated compounds is minimized. To insure low moisture content, these electrodes are dried at higher temperatures during manufacture than are conventional electrodes. Because the coatings have low moisture content, the weld metal deposits of these electrodes are low in hydrogen content. Potassium silicate, calcium carbonate and titania are used in the E6016 coverings in rather large amounts. As a result, the E6016 electrodes are suitable for welding with alternating current and direct current, reverse polarity. The excellent fluxing characteristics of the materials in these coatings, in combination with the low moisture content, help produce deposits of excellent soundness and mechanical properties.

Because the coverings of E6020 electrodes are very high in mineral content and very low in cellulose, there is little tendency for breakdown during welding. This characteristic makes the electrode suitable for operation at high current and high speed. However, the combination of materials in the E6020 coverings produces a highly fluid weld metal, which makes it unsuitable for anything but horizontal-fillet and flat-position welding. The weld metal has excellent mechanical and radiographic properties.

The E6024, E6027 and E60xx electrodes have the characteristics of the basic types after which they are patterned, except that the combination of the added iron powder and the relatively thick coverings permits higher welding speeds and easier application. E6024 is similar to E6012 plus iron powder, E6027 to E6020 plus iron powder, and E60xx to E6016 plus iron powder.

Effect of Moisture in the Coatings

It is often mistakenly considered that moisture is harmful in the coverings of all mild steel electrodes. Precaution is usually taken by fabricators to store the electrodes in dry places and this practice should certainly be encouraged. However, to redry electrodes, as is often done after prolonged periods of storage, may be quite harmful, especially to the E6010 and E6011 electrodes. Redrying may impair both quality and operational characteristics of the cellulose types.

The electrode manufacturers normally produce these electrodes with a controlled moisture content, designed to fall between 3.0 and 5.0% for E6010 and in a somewhat lower range for E6011. Therefore, a practice of redrying that lowers the moisture content below the designed amount is not recommended. Usually, all other types of electrodes operate best when the moisture content is lowest. The temperature and time used for drying are not the same for all types of electrodes; they depend on the coating composition and thickness. Coatings containing organic material are usually dried at temperatures below the charring point, about 450 F, whereas the inorganic coatings, such as the low-hydrogen types, may be dried at temperatures up to 800 F.

The moisture content may be determined on all types except the low-hydrogen E6016 and E60xx electrodes by weighing a sample of approximately one gram of the coating before and after redrying in an electric oven at 220 F for 1 hr. The loss in weight calculated in percentage is the moisture content.

Moisture content for the low-hydrogen types (E6016 and E60xx) is usually determined at 2400 F. This process requires special apparatus and technique. The method is described in the military specification MIL E986 and in The Welding Journal for August 1950, page 629.

Table VI may be used as a guide for optimum moisture values in the various

Table V. Typical Constituents Used in Electrode Coatings

Constituents of Coating	Electrode Class									
	E6010	E6011	E6012	E6012X	E6013	E6016	E60xx	E6020	E6024	E6027
Cellulose	X	X	X	...	X	...	...	X	X	X
Rutile	...	...	X	X	X	X	...	...	X	...
Feldspar	...	...	X	X	X	...	...	X	X	X
Asbestos	X	X	X	...	X	...	...	X	X	X
Mica	...	...	X	X	X	...	...	...	X	...
Silica	...	...	...	...	...	...	...	X	X	X
Calcium carbonate	...	...	X	X	...	X	X	X	X	X
Ferromanganese	X	X	X	X	X	X	X	X	X	X
Sodium silicate	X	...	X	X	...	...	...	X	X	X
Potassium silicate	...	X	...	...	X	X	X	...	...	...
Fluorspar	...	...	...	...	...	X	X	...	...	...
Titanium dioxide	X	X	...	...	...	X	X	...	...	...
Iron oxide	...	...	...	...	...	...	...	X	...	X
Manganese oxide	...	...	...	...	...	...	...	X	...	X
Iron powder	...	...	...	...	...	...	X	...	X	X

Table VI. Recommended Moisture Content of Coatings and Redrying Procedure

Electrode Class	Recommended Moisture Content, %	Drying Procedure Temperature, deg Fahr	Drying Procedure Time, hr
E6010	3.0 to 5.0	250	0.5 to 1.0
E6011	2.0 to 4.0	250	0.5 to 1.0
E6012	<1.0	350	1.0 to 2.0
E6012X	<1.0	350	1.0 to 2.0
E6013	<1.0	350	1.0 to 2.0
E6016	<0.4	500 to 700	1.0 to 3.0
E60xx	<0.4	500 to 700	1.0 to 3.0
E6020	<1.0	350	1.0 to 2.0
E6024	<0.5	350	1.0 to 2.0
E6027	<0.5	350	1.0 to 2.0

types of electrodes. It must not be assumed, however, that some brands or types of electrodes will not operate satisfactorily and produce satisfactory weld metal deposits when the moisture content of the coating falls outside these ranges. The E6010 and E6011 types, for example, may be satisfactory even if the moisture content exceeds these values, provided the coating does not blister during welding and interfere with operation of the electrode.

The quality of the weld metal is not impaired by excess moisture if the operation of the electrode remains satisfactory. However, when most brands of these types are dried much below 2.0%, there is more spatter, greater tendency for porosity, and the arc control may be impaired. Also, the moisture content of E6010 electrodes may be decreased to values lower than the recommended level when the container is left open and exposed to a hot, dry atmosphere.

It is desirable to keep the moisture content of low-hydrogen coatings below approximately 0.4%. If the moisture content is much above this value the weld metal may be porous or cracked. Since moisture is so critical in these types, electrodes should not be allowed to remain in open boxes or storage bins. A safe practice followed by many fabricators is to return all unused electrodes exposed for 4 hr or more, or at the end of a working shift, to a drying oven maintained at 350 to 450 F for at least 8 hr before reissuing them.

Moisture absorption data for a typical E6016 electrode for a humid condition (85% relative humidity at 85 F), a medium humid condition (67% relative humidity at 85 F) and a relatively dry condition (52% relative humidity at 85 F) are given in Fig. 9.

Figure 10 shows the moisture loss at various temperatures in a well-ventilated oven for a typical E6016 electrode.

Although moisture absorption and loss may vary with different brands of electrodes, the data given in these graphs are representative of the commercial electrodes available today (August 1955).

The procedure and conditions required to restore E6016 electrodes of a typical commercial brand to their original usability after they have absorbed a harmful amount of moisture (the amount necessary to cause porosity or cracking in the weld metal) are as follows:

Dry in a well-ventilated oven by bringing the temperature up slowly to between 500 and 700 F for approximately 1 hr. Prolonged drying periods (weeks or months) at either lower or higher temperatures may cause the coating of some brands to become brittle and crack. Electrodes stored in open containers will not absorb a harmful amount of moisture if the relative humidity for room temperature is 50% or less. If temperature only is controlled, 150 F is high enough to prevent harmful amounts of moisture absorption and 175 F should not be exceeded.

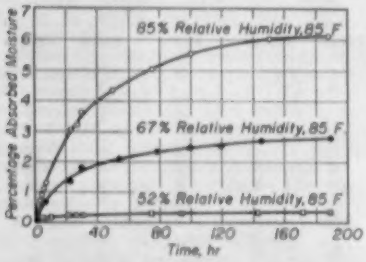


Fig. 9. Moisture Absorption by a Typical E6016 Electrode

Iron Powder Coatings

The use of iron powder in electrode coatings is comparatively new and most electrode manufacturers now supply electrodes that meet the tentative specifications for these rods. There is still considerable variation among the electrodes supplied by different sources and it is recommended that, before rejecting or accepting iron powder electrodes for production use, sample lots from different manufacturers should be tested extensively under conditions of production fabrication.

Because of the electrical conductivity or high current-carrying capacity, and the ease of handling the iron powder electrodes, it is difficult to prevent the operators from using excessively high currents that may result in poor or defective welds. This is important where various types of incentive pay are in force and necessitates closely controlled welding procedures to insure proper quality. Using too high welding current may impair strength and ductility and cause porosity in the weld.

Selection of Electrodes for Maximum Welding Speed

The selection of an electrode that will give maximum welding speed consistent with requisite quality depends on fit-up, ability of the electrode to fill behind the arc, position of the joint to be made, and on a number of other factors.

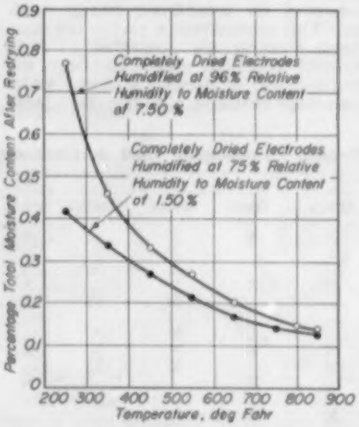


Fig. 10. Redrying Characteristics of a Typical E6016 Electrode

Effect of Fit-Up. Figure 11 shows the influence of various sizes of gaps on welding speeds. The care needed in cutting, forming and handling of shapes to be welded to avoid poor fit-up is a major factor in the cost of welding. A gap of 1/64 to 1/32 in. will prevent angular distortion and weld cracking. For example, a square-edge or single-V butt weld on ½-in. plate, when welded with a 1/32-in. gap, can be made more than twice as fast as the same weld with a 3/16-in. gap.

Although Fig. 11 is for butt welds only (either square or grooved), fillet welds are affected by oversized gaps in a similar manner. A fillet weld equal in strength to a 7/16-in. conventional fillet can be made at 12 in. per min with a 1/32-in. gap, but at only 8 in. per min with a ¼-in. gap. A gap of 3/16 in. will require multiple-pass welding and the speed will drop to about 3 in. per min.

On one job involving a horizontal fillet in a lap joint with 0.090-in. plates placed in the vertical plane, the following steps came as a result of improved techniques and electrode development:

1 Originally, 5/32-in. E6012X electrodes were used at a speed of 50 in. per min. A change to 3/16-in. electrodes resulted in a decrease of approximately 15% in welding time on each assembly with a 10% saving in electrode cost and an improvement in quality. These benefits resulted from decreased time for changing electrodes and improved utilization of electrodes.

2 It was found that 7/32-in. special E6012X electrodes at 80 in. per min would produce a weld of higher quality than had been possible with the 3/16-in. electrode at 60 in. per min. These electrodes were used with the drag technique.

In evaluating electrodes for this oper-

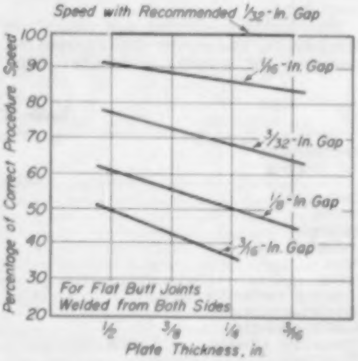


Fig. 11. Effect of Fit-up on Welding Speed of Downhand Butt Joint (Square or Grooved) of Various Plate Thicknesses

Table VII. Comparison of Welding Characteristics of Special E6012X Electrodes of 3/16-In. Diam

Electrode Brand	Number of Runs[a]	Length of Weld, in.[b]	Ability to Fill[c]	Appearance of Bead[d]	Stub Length, in.[e]	Percentage Shorted[f]	Vertical Operation[g]
X	20	43.04	Good	Good	1.96	20	Good
Y	7	43.18	Very Good	Good	1.88	0	Fair
Z	3	38.83	Poor	Undercut	3.33	100	Good

(a) The number of horizontal weld specimens made in the electrode-feed device (Fig. 12) with each brand of electrode submitted for test. The data in columns 2 through 6 were obtained from these specimens. At least six specimens were made from each brand of electrode that seemed to be acceptable.

(b) The average length of weld, in inches, produced from one 14-in. elecrode in the electrode-feed mechanism under the following welding conditions: 330-amp ac; welding speed, 60 in. per min; force on electrode into the joint, 33 oz; electrode angle, 20 deg from horizontal; joint-to-electrode angle, 68 deg.

(c) Continuity of weld bead: a rating of "very good" is for beads that averaged less than one hole where the weld metal separated; those rated "poor" averaged seven or more holes per specimen.

(d) The visual appearance of the weld as to contour and undercut on specimens made with the electrode feed device. The most desirable fillet weld is one with a flat bead and good fusion at both edges.

(e) The average length, in inches, of the unused portion of the electrode after the weld was completed. The electrode-feed device was positioned so that if the electrode did not short out against the workpiece, the stub was 1.88 in. long when the weld was completed.

(f) Percentage of electrodes tested in the electrode-feed device that did not burn down to 1.88-in. stub.

(g) This characteristic was classified by the weld appearance and the operator's skill required on a 12-in. specimen manually welded vertically down with 330-amp ac using the drag technique at travel of approximately 50 in. per min. Several specimens were made for each brand of electrode tested.

ation, the testing method to be described was developed to compare electrodes under conditions that had been determined to be applicable to the production operation. With all such tests the results must be continually cross-checked with the actual job problems.

It was found that manual manipulation of the welding electrode often produced variations resulting from operators' individualities, rather than from the characteristics of the electrode being tested. Since the electrodes under test were for use with the drag technique (which requires only a forward pressure of the electrode into the welding groove, and movement of the electrode in relation to the joint) a mechanism was devised that would eliminate the human element in the test. This was done by mounting an assembled joint on a travel carriage to move it at a constant speed past the test electrode that was mechanically forced into the groove at a given pressure (Fig. 12). All tests of horizontal fillet welding reported in Table VII were made with this device.

The carriage of the testing device (Fig. 12) had a speed adjustable from 7 to 210 in. per min, with an extension bolted to its side for attaching the test specimen. The electrode-feeding mechanism consisted of an inclined ⅝-in. square steel bar supported by two sets of rollers mounted on ball bearings. The forward end of this bar had a clamp for gripping the bare end of the electrode. Steel wires (0.016-in. diam) attached to the rear end of the square bar supported the weights that were to be applied to the bar to give a forward thrust to the electrode. The electrode was held in the apparatus by passing its forward end through a guide slightly larger than the electrode diameter. This insured that the electrode would remain in the proper position in relation to the lap joint. The entire electrode-feed mechanism could be rotated horizontally and vertically to bring the electrode into the joint at any desired angle.

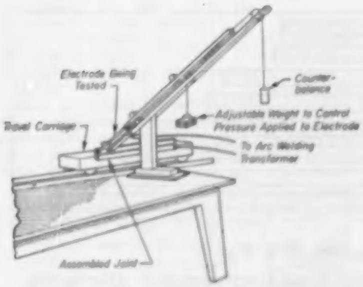

Electrode Being Tested
Counter-balance
Adjustable Weight to Control Pressure Applied to Electrode
Travel Carriage
To Arc Welding Transformer
Assembled Joint

Fig. 12. Device for Testing Electrodes

A 500-amp a-c welding transformer with an open circuit voltage of 78 was used for the tests. The time of current flow for each weld specimen was obtained by a time meter actuated by a relay in the welding circuit. The length of weld was measured on all specimens. With the welding time and the length of weld known, an accurate value of welding speed could be obtained for each specimen. The test specimens duplicated the condition of the production material.

The lap joints were formed of two pieces of 0.090-in. steel, preassembled and held together by spot welds. In the early tests, the joints were 48 in. long; later when tests were made of electrodes of larger diameter, the length of the specimen was increased to 60 in.

Table VII and the associated explanatory notes indicate the type of data obtained from this test. (The few selected examples of data are representative of results on more than 50 electrodes evaluated by this method.)

This detailed example has been presented to illustrate the importance of completely investigating the various characteristics of an electrode for optimum application to a particular job. Two of the electrodes included in Table VII show good all-around performance while the third is poor for this particular application. It is only for large-volume applications that detailed tests of an electrode such as those described can be justified, since closest coordination between the test and the production job is essential if the results are to be of value.

Effect of Welding Position

Whenever possible, the work should be positioned so as to attain the greatest welding speed, provided the cost of positioning fixtures is justified. The order of preference for speed is: flat, horizontal, vertical, and overhead for fillet welds; and flat, vertical, horizontal, and overhead for groove welds.

Flat and Horizontal Fillet and Lap Welds. The speed relationships given in Table VIII hold also for other diameters of the same types of electrodes, and selection can be made on this basis. However, all selections should be verified by making tests of welding speed under shop conditions with production steel before final decisions are reached.

Table VIII gives the speeds attainable in making ¼-in. horizontal fillet welds using 3/16-in. conventional electrodes and 5/32-in. iron powder electrodes. The smaller size of iron powder electrode was chosen for the comparison because almost the same weight of metal is available for deposition per inch of electrode from a 5/32-in. iron powder electrode as from the 3/16-in. conventional electrode.

Although the 3/16-in. size was chosen for these comparisons, 7/32 and ¼-in. electrodes can be used for higher speeds. The amperages given represent the top, bottom and middle of the pre-

Table VIII. Linear Speed on ¼-In. Horizontal Fillets for Mild Steel Electrodes

Direct Current Amp	Direct Current Speed,[a] ft per hr	Alternating Current Amp	Alternating Current Speed,[a] ft per hr
	E6010, 3/16 In.		
160	27.8	...	...
170	29.3	...	...
180	31.2	...	...
	E6011, 3/16 In.		
160	27.6	170	30.5
170	28.6	180	32.8
180	29.6	190	34.8
	E6013, 3/16 In.		
200	32.8	220	34.6
220	37.2	240	39.1
240	42.9	260	42.9
	E6012, 3/16 In.		
200	30.8	220	36.6
220	36.9	240	40.9
240	42.9	260	46.4
	E6020, 3/16 In.		
200	51.5	220	52.1
220	59.5	240	57.5
240	66.7	260	64.1
	E6016, 3/16 In.		
200	33.1	220	36.2
220	35.2	240	38.5
240	37.5	260	43.5
	E6024, 5/32 In.		
200	68.9	220	69.4
210	71.8	230	73.5
220	75.8	240	78.1
	E60xx, 5/32 In.		
200	44.4	220	48.9
210	47.0	230	50.8
220	50.5	240	53.1
	E6027, 5/32 In.		
200	60.7	220	64.3
220	68.0	240	72.6
240	73.9	260	78.3

(a) For 100% arc time

ferred range of current for each type. (The range may vary somewhat for different brands of electrodes.) To move outside the preferred current range ordinarily means some sacrifice in weld-metal characteristics or appearance of deposit. Certain types of electrodes produce welds of greater convexity than others, and, as the weld becomes more convex, less footage of fillet weld is obtained in a given arc-time.

Results for single-pass flat and horizontal lap welds and single-pass flat fillet welds of ¼-in. size would be closely similar to the results shown for horizontal fillets.

Vertical Fillet and Groove Welds. Figure 13 gives the relative footage of 5/16-in. vertical up fillet weld that can be produced in an hour of arc-time with 3/16-in. mild steel electrodes using direct current. The amperage used for these tests is considered maximum for the electrodes represented. Results for alternating current would be much like the pattern given in Fig. 13.

In most vertical welding the electrode is continually pulled away from the molten pool, but without extinguishing the arc and yet long enough for the pool to solidify before another mass of weld metal is deposited. The faster and flatter the pool solidifies the faster the welder can move the electrode back into the pool to deposit more metal. Some welders take advantage of the fast solidification of E6010 and E6011 electrodes and employ a fast whipping technique referred to in Fig. 13 as "rapid technique". In making vertical groove welds, the relative speeds that can be attained with the same electrodes are as shown in Fig. 13.

Horizontal-Butt and Overhead Groove Welds. When electrodes are used for making horizontal-butt and overhead groove and fillet welds, their speed pattern will ordinarily follow that of vertical fillet welds (Fig. 13).

The electrodes represented in Fig. 13 will produce about 27 ft of 3/16-in. fillet weld per hour of arc-time in the overhead position and about 20 ft of ¼-in. fillet in the same position.

Flat Groove Welds. In general, speed in making flat groove welds depends directly on the deposition rate of the electrode. The relative deposition rates of the various types of electrodes for direct-current and alternating-current welding are given in Fig. 14 and 15.

Selection of Electrodes for Least Total Cost

The form for comparative cost studies in Table IX indicates the data normally used to compare electrodes for lowest cost. The three principal factors that affect the cost are arc-speed (labor), amount of electrode used (weld bead shape), and the cost per pound for the electrode. The factor of power cost cancels out because it is approximately the same for all applications. The final selection of electrodes for a given application depends on the many other considerations discussed in preceding sections of this article, as well as on those listed in Table IX.

The cost of welding an assembly can be calculated from welding-rate data derived from the welding of test specimens using the proposed welding method. A weighed quantity of electrodes is used to make the test weld on a specimen that is weighed before and after welding. During the test the arc-time is measured with a stop watch. The time required to make an inch of weld and the amount of electrode used for an inch of weld can be calculated from the test data. If labor and electrode costs are known, cost per inch of weld can be determined.

An Example illustrating the use of this method is as follows: An assembly requires 250 in. of horizontal weld in a ¼-in. fillet. Two electrodes have been proposed: ¼-in. E6013 and 3/16-in. E6024 iron powder electrode. The problem is to determine which electrode is more economical.

An arbitrary figure of $2.10 per hr is used for the cost of direct labor. The charge for direct labor is usually entirely precise; computation of overhead charges varies greatly with companies. Some divide overhead into two classes: fixed overhead, which does not vary with direct labor; and variable overhead, which does. With this method, variable overhead per man-hour is added to the cost of direct labor and may nearly double the labor charge. Since labor is the major cost of welding, the method used for handling these charges often determines which electrode is least expensive in production.

Some companies use only the rate paid for direct labor, on the basis that if the number of man-hours on a given job is reduced, there is no change in actual expenditures for overhead items.

Make-ready for welding and handling of the work require the welder's time. These nonwelding activities may include: hoisting pieces, locating work in fixtures, operating the weld positioner, moving parts, handling the welding equipment, moving ladders, changing electrodes, tacking and cleaning welds. A value derived from experience in the field can be assigned to each of these items. Their total contribution to cost, although an important factor, may or may not change with the type of electrode used. In this example, 16 min per assembly is charged for these non-welding activities.

The time required to make an inch of weld can be determined by two methods: (1) timing the weld, measuring the length of weld and calculating the time for each inch of length. This method is simple, but gives inconsistent results because of the difficulty of holding weld size. (2) Consistently accurate results can be obtained by determining the weight of the deposited metal per unit time and dividing this by the weight of an inch of dimensionally perfect weld to find a calculated length. The weight of an inch of fillet weld for this calculation is obtained by multiplying the volume of a ¼-in. fillet 1 in. long (0.25 × 0.25 × 0.5 × 1 in.) by the weight of a cubic inch of steel (0.283 lb), which

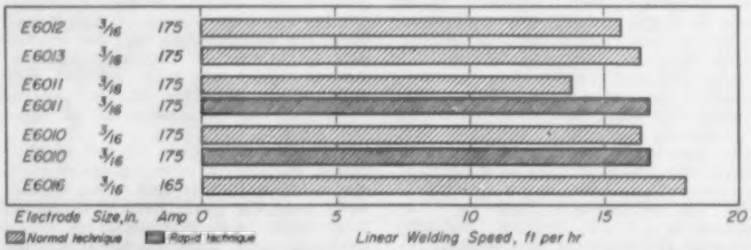
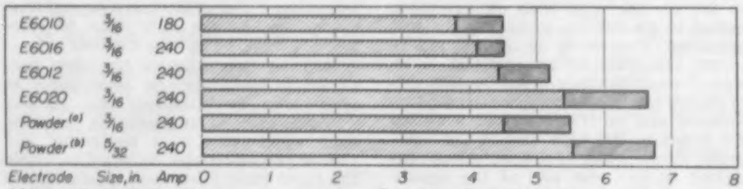
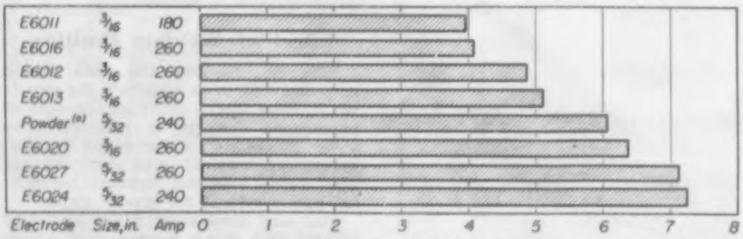


Fig. 13. Typical Linear Speed on 5/16-In. Vertical Up Fillets for Mild Steel Electrodes, DC



(a) Iron powder, low-H, all position
(b) Iron powder, low-H, horizontal and flat

Fig. 14. Typical Deposition Rates for Mild Steel Electrodes with Direct Current. Data are for flat groove welds. Heavily crosshatched portions indicate differences among average results of several different brands.



(a) Iron powder, low-H, horizontal and flat

Fig. 15. Typical Deposition Rates for Mild Steel Electrodes with Alternating Current. Data are for flat groove welds.

equals 0.00884 lb per in. of ¼-in. fillet.

Specimens for checking the welding speed and the consumption of the two types of electrode were made by tacking together two pieces of plate to form a T-section. A specimen was welded with each type of electrode; three electrodes were used for each test. The weight of the test specimens before and after welding, the weight of electrodes, and the arc time were recorded. Data for the tests and cost calculations are given in Table X.

This method is simple and straightforward and does not require extensive tests. Its disadvantage is that all items that may vary with the choice of electrode cannot be evaluated without experience on similar jobs or additional data collected on the actual job.

In this example, data on cleaning costs are not presented. Chipping out and repairing of defective welds is a costly item that frequently is overlooked. If one electrode has a greater tendency to produce rejectable defects, the cost of chipping out and repairing the defects should be charged to welding of the assembly. This is often a major cost item that influences electrode selection.

Another requirement is the ease of operation or the skill required to use the electrode. For example, a skilled operator might produce a horizontal fillet weld of good quality with a high-production electrode. An inexperienced welder might require a slower electrode to produce a fillet of equal quality and free from undercutting.

The cost of maintaining inventories of a number of different types of electrodes often limits the selection problem in a given shop.

Selection Based on Laboratory and Field Tests

Tests for selection of electrodes should be made under both laboratory and field conditions. Seven examples are cited here to illustrate why both kinds of tests are necessary.

Table IX. Form for Comparative Study of Welding Costs

Item	Entry
Cross section of joint	
Dimensions, gap and fit-up (Consideration should be given to advantages in reducing weld size if penetration or weld strength is improved.)	
Electrode, size, make, class and type, using the best size for each job.	
Current(a) and polarity (best current and polarity for each electrode; this will not be the same for both.)	
Arc-speed, in. per min (at highest usable current for each electrode)	
Arc-speed, ft per hr	
Arc-speed × % "operating factor"	
Actual arc-speed, ft per hr	
Electrode used, lb per ft(b)	
Electrode cost per lb	
Labor and overhead cost per hr	
Total cost per ft(c)	

(a) Cost of power has been eliminated as being approximately the same in all tests and too small to consider.

(b) Total rod (in lb) used, including stub.

(c) $\frac{\text{Total cost}}{\text{ft}} = \frac{\text{Electrode cost}}{\text{ft}} + \frac{\text{Labor and overhead}}{\text{ft}}$

Example 1. In one welding job on a pressure vessel, considerable difficulty was encountered with joints on structural steel, some alloy and some plain carbon. Laboratory tests indicated that a cellulose type of electrode, such as E6010 or E6013, would be preferable, both for cost and quality. Since most of the steel was more than ⅜-in. thick, it was decided to use the E6013 electrode for welding the mild steel portion. A low-hydrogen E8016 was selected for the alloy steel.

As soon as the welded joint was completed in the field, it was radiographed. Although some of the welded joints met the radiographic requirements, others failed because of excessive porosity. The electrodes were checked by both the manufacturer and the user but no deficiency could be discovered. Some of the electrodes made good welds while others from the same package did not. After the electrodes were thoroughly tested in the laboratory, it was decided that the coating and the atmospheric conditions were contributing to the trouble.

Since the alloy steel was to be welded with the E8016 low-hydrogen electrodes, trained and qualified welders were available to try the E8016 low-hydrogen electrode on the mild steel. Excellent results were obtained in the field in winter weather, high winds and other adverse conditions. The electrodes were stored in an oven at 400 F, and no welder was allowed to use any electrode that had been out of the oven more than 4 hr. The welder was also given good protection from the wind. The radiographs proved that consistently good results were secured when proper procedures were followed. The actual welding time was increased by using the low-hydrogen electrodes, but the overall cost with these more expensive electrodes was satisfactory since the high costs of repairs and re-radiographing were eliminated.

This same situation developed on another structure for which the joints were to be welded with E6010. The costs of making repairs to the weldment and re-radiographing the repairs were greater than the added cost from using the low-hydrogen electrodes. Again it was found that some of the E6010 electrodes gave satisfactory results while others of the same allotment did not. All the electrodes successfully passed the procedure qualification standards as required by the ASME Code, but did not consistently pass the radiographic requirements in the field.

Example 2. A typical cost analysis using either the E6010 or E6013 versus the low-hydrogen electrode is:

Let 1.0 equal the cost of E6010 or E6013 electrode plus cost of depositing 1 ft of butt weld. Then:
1.5 = the cost of low-hydrogen electrodes plus the cost of depositing 1 ft of butt weld
5.0 = the cost of radiographing 1 ft of complete weld
2.0 = the cost of repairing 1 ft of defective weld using E6010 or E6013
3.0 = the cost of repairing 1 ft of defective weld using the low-hydrogen electrodes

Table X. Analysis of Welding Costs Computed from Rate of Welding

Data on Assembly to be Welded

Length of ¼-in. fillet weld specified on assembly drawing	250 in.
Labor cost per hour	$2.10
Labor time other than welding time required to make weld	16 min
Weight of linear inch of ¼-in. fillet weld	0.00884 lb

Data on Welded Specimens

	3/16-In. E6024 Electrode	1/4-In. E6013 Electrode
Electrode cost per lb	$ 0.18	$ 0.135
Weight of 3 electrodes	0.810 lb	0.931 lb
Weight of tacked specimen	10.00 lb	10.10 lb
Weight of specimen after welding	10.56 lb	10.72 lb
Weight of deposited metal	0.56 lb	0.62 lb
Arc time to make weld	3.85 min	5.32 min
Theoretical length of weld made	$\frac{0.56}{0.00884} = 63.3$ in.	$\frac{0.62}{0.00884} = 70.1$ in.
Pounds of electrode used per inch of weld	$\frac{0.810}{63.3} = 0.0128$ lb per in.	$\frac{0.931}{70.1} = 0.0133$ lb per in.
Cost of electrode to make inch of weld	0.0128 × 0.18 = $0.0023	0.0133 × 0.135 = $0.0018
Minutes required to make an inch of weld	$\frac{3.85}{63.3} = 0.0608$ min per in.	$\frac{5.32}{70.1} = 0.0759$ min per in.
Labor rate per min	$\frac{2.10}{60} =$ $0.035 per min	$\frac{2.10}{60} =$ $0.035 per min
Labor cost per inch of weld	0.035 × 0.0608 = $0.00213 per in.	0.035 × 0.0759 = $0.00266 per in.
Total arc-time cost per inch of weld	Labor $0.00213 Rod 0.00230 $0.00443 per in.	Labor $0.00266 Rod 0.00180 $0.00446 per in.
Arc-time cost for welding assembly	250 × 0.00443 = $1.11	250 × 0.00446 = $1.12
Cost of labor other than arc-time	0.035 × 16 = $0.56	0.035 × 16 = $0.56
Total cost of welding assembly	$1.11 0.56 $1.67	$1.12 0.56 $1.68

Note: Although the cost of welding an assembly is the same, a welder working with ¼-in. 6013 electrodes can produce four assemblies in 4 × 18.98 = 75.92 min of arc-time, while a welder working with 3/16-in. iron powder electrodes can produce five assemblies in 5 × 15.20 = 76.00 min of arc-time.

From experience and data secured on the job described in example 1, the repairs and re-inspections amounted to about 20% of the footage when using E6010 or E6013 electrodes, and only about 5% when using low-hydrogen electrodes. The cost of welding, x-ray inspection, repairing and repeating the x-ray inspection of 100 ft of welding is:

Original weld	100 x 1.0	100.0
Original x-ray	100 x 5 x 1.0	500.0
Cost of repairs	0.20 x 100 x 2.0	40.0
Cost of re-x-ray	0.20 x 100 x 5.0	100.0
	Total cost	740.0
	Cost per foot	7.4

The cost of welding, x-ray inspection, repairing and reinspecting for 100 ft of welding made with low-hydrogen electrodes is:

Original weld	100 x 1.5	150.0
Original x-ray	100 x 5.0	500.0
Cost of repairs	0.05 x 100 x 3.0	15.0
Cost of re-x-ray	0.05 x 100 x 5.0	25.0
	Total cost	690.0
	Cost per foot	6.9

From the above analysis it is clear that when welds must meet radiographic requirements, the cost of completing an acceptable weldment is less with low-hydrogen electrodes. However, it must be realized that the cost of protecting the weldments from the wind and other atmospheric conditions have not been taken into account. This cost may vary considerably depending on the shop or field conditions encountered and must be estimated carefully before an accurate value can be determined for total cost.

Example 3. The cost of electrodes is usually important in all high-production welded assemblies. For such applications, it is always necessary to select the electrode that has the fastest welding speed and yet fulfills requirements of appearance, penetration, porosity, or strength, with the available equipment.

The data relevant to electrode selection in this example are: (1) weld metal with properties equivalent to 1020 steel; (2) appearance of secondary importance; and (3) electrode satisfactory for the steels of higher sulfur content, such as 1115.

The only electrodes that will weld 1115 steel bars satisfactorily are the low-hydrogen types. These include E6016 and the more costly stainless steel electrodes. Both of these electrodes will satisfy any of the above conditions at similar speeds. Thus, the only other consideration is electrode cost, so the cheaper electrode, E6016, is selected.

Example 4 concerns a joint for which selection of electrode was based almost entirely on performance of the electrode in laboratory and production tests. This joint occurs on a truck cab where the side sill is welded to the body-lock pillar.

E6013 was first selected as the most satisfactory type of electrode. Laboratory tests were then run to determine the ability of different brands of E6013 to give a satisfactory weld on a sample section. Fit-up was varied and all samples were welded in vertical down position, using production steel. Two brands of E6013 passed all test requirements and were selected. When used in production, both these electrodes proved satisfactory, confirming results from the laboratory.

Example 5. Another example in which selection of electrode was based on field and laboratory tests concerns the experience of a fabricator who wanted to increase his welding output. About 70% of the welding was fillet welding. A particular brand of E6012 had been in successful use for 3 yr but increased production was considered necessary. Tests were made of deposition rate on 12 brands of E6012 electrodes in the laboratory by depositing weld beads on a flat plate and measuring the time required for depositing 12 in. of a 3/16-in. electrode. The 3/16-in. electrode that had been in use previously ranked ninth in the laboratory test.

When the electrode that ranked first in the laboratory test was tried in the shop, welds cracked because of diffusion of alloying elements from the basic steel into the weld. This threw doubt on the dependability of results obtained in the laboratory, so all electrodes tested in the laboratory were tested in the shop under normal conditions with production steel. Under these conditions crack-free welds could be produced with only three of the electrodes tested and of these three, more footage of satisfactory weld was obtained in a given time with the electrode that had been used in the shop previously.

The fact that the fabricator returned to the original electrode is of only casual interest; the principal value of the example is in showing that only tests made under shop conditions with production steel were capable of showing which electrode would give the greatest footage of satisfactory weld in a specified time.

Example 6. Several pressure vessels used in a typical refining operation required modification by insertion of patches into their shells. The internal diameters of the vessels were from 4 to 5 ft, and wall thicknesses were between 3 and 5 in. The thickness of the insert patch was 2½ in.; the patch diameter was between 16 and 18 in., depending on the extent to which previous welds and repairs could be removed. The vessels were made from plain carbon steel with less than 0.30% C.

A previously repaired vessel was welded with E6010 electrodes following a preheat above 400 F to prevent weld cracking. Since the high preheat made operating conditions difficult for the welders, the type selected was E6016, based on the results of laboratory tests for mechanical properties of all-weld-metal specimens and usability tests for position welding. It was found that E6016 required less preheat than had been used previously and produced sounder welds with considerably less cracking.

Example 7. An evaluation of deposition rates such as shown in Table XI is often valuable in selecting an electrode. Electrode cost is a small item in final cost of a completed weldment; labor is the big item. However, if production arc welders are provided with a fast electrode (with high efficiency in deposition and hence low spatter loss), proper electrode selection results in lower total cost of welding.

For example, with five brands of 3/16-in. electrodes at 200 amp, deposition rate (lb per hr) ranged from a low of 4.2 to a high of 5.3, or a difference of 1.1 lb per hr of weld metal laid in the joint. Thus the slowest electrode is 20% slower than the fastest.

Spatter loss for the different electrodes at 250 amp varied from 6.1 to 20.8%. The electrode with a 20.8% spatter loss broke at 250 amp, and this was reflected in low efficiency in deposition and low rate of deposition.

Welding Galvanized or Cadmium-Plated Steel

Many of the usual selection factors are not applicable to the choice of electrodes for welding galvanized or cadmium-plated steel. Here the problem is reduced to the simple requirement that the coating must be removed as completely as possible before the weld metal is deposited, primarily to obtain a sound weld and also to avoid possible embrittlement of the base metal under stress. If the zinc or cadmium is not removed by mechanical or other means, selection of electrodes is limited to E6010 or E6011, which have deeply penetrating arcs capable of burning off the coating that obstructs deposition of the weld. Adequate ventilation is required to remove the smoke and fumes. Cadmium fumes are poisonous (see page 755 of the 1948 Metals Handbook).

The choice between E6010 and E6011 depends on the power source available and, to some extent, on the shape of the weldment. Either electrode will produce relatively sound welds with full penetration. The E6011 with alternating current is less subject to arc blow. This may be important if internal corner welds are involved. Both electrodes are usable in all positions and speed of welding is usually not important.

For fabrication involving a coated part to be attached to a plain steel plate, where a sound weld of good appearance is required, it is still necessary to burn off the coating before good fusion is obtained. E6010 or E6011 is used to do this at normal welding speeds. If a higher speed is required, the welding current can be increased or electrodes of larger diameter of the same types may be used. The extent to which this is feasible depends on the joint design, the position of welding, and the size of weld permitted.

It must be recognized, of course, that welds made on galvanized and cadmium plated steel will have no coating and are unlikely to be protected against corrosion by the adjacent coating on the plated part. If a protective coating over the weld is required, the steel is welded before galvanizing or plating. In such an application the selection of electrodes is based on the usual factors for the type of weldment involved.

Table XI. Selection of Electrodes on the Basis of Deposition Values
(Tests on 3/16-in. E6012 electrodes)

	Range of Results (Five Brands)		
	200 amp	225 amp	250 amp
Melt-off rate, in. per min	9.7 to 12.4	11.0 to 13.0	11.7 to 13.7
Deposition rate, lb per hr	4.2 to 5.3	4.7 to 5.3	4.7 to 5.8
Deposition efficiency, %	76.9 to 82.0	73.7 to 81.5	62.8 to 80.5
Spatter loss, %	4.0 to 5.9	5.1 to 9.9	6.1 to 20.8

Metal Cleaning Costs

By the ASM Committee on Cost of Metal Cleaning

THIS ARTICLE deals with the elements of cost in metal cleaning processes. The principal items of expense considered are: direct labor, labor for disposal of cleaning wastes, water, other material, energy and maintenance.

Direct Labor

Direct labor necessary to operate the various cleaning processes, including charging and emptying of tanks, will vary considerably with the extent of mechanization of the process. In the table of approximate cost relations, Table I, direct labor is based on the following assumptions.

Vapor Degreasing. The direct labor in this operation is evaluated on the basis of one-tank operation and includes placing the parts in the degreaser and also unstacking.

Solvent Cleaning costs are for a single-tank operation, similar to that for vapor degreasing.

Hot Tank Alkaline Cleaning is evaluated on the basis of three tanks (alkaline, cold and hot water tanks). Because of the three operations, labor value is slightly higher than for a single tank.

Cold Spray Alkaline Cleaning is usually done in one tank and is of short duration.

Hot Spray Alkaline Cleaning. Labor for this method is similar to cold spray alkaline cleaning.

Electrolytic Alkaline Cleaning usually requires the same number of tanks as hot tank alkaline cleaning.

Hot Tank Emulsion Cleaning. This operation usually requires only one tank without any subsequent rinses, and the handling will be about the same as for other one-tank operations.

Hot Spray Emulsion Cleaning is similar to alkaline spray (hot and cold).

Acid Cleaning (Sulfuric Acid). This method is evaluated for a four-tank operation (acid pickling, cold and hot water rinses and oiling). Because of the longer duration of the cleaning cycle and the greater number of operations, it will have about the highest direct labor costs of any of the methods.

Abrasive Cleaning. The direct labor includes the handling of the metal and the grit or abrasive and also the cleaning of the dust collectors.

Labor for Waste Removal

The labor cost for waste removal, as used in Table I, pertains to the cleaning of tanks, the transferring of sludge to the disposal area, but not repair maintenance. The cost for waste disposal is not included in the table, since disposal and waste treatment vary with the pollution abatement ordinances observed in different localities. A few of the factors that affect the cost of waste treatment and disposal are mentioned in the following paragraphs to illustrate the necessity for a careful appraisal.

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Vapor and Solvent Degreasing. The solvent can be recovered by distillation, and the soil that remains may be disposed of on dumps or it may be incinerated. The latter procedure is often preferred because some wastes are toxic, subject to spontaneous combustion, or have other objectionable properties that make them a hazard and a liability on either a public or private dump.

Alkaline and Emulsion Cleaning often involve a water rinsing operation that transfers the soil and oily emulsions to a quantity of water. These waste waters, when ready for treatment, are usually highly alkaline and high in oil content. The economics of disposal depends on the degree of treatment required, which, in turn, depends on where the waste is to be discharged. The municipal sewage treating systems of some large cities can take considerable amounts of highly concentrated waste. Many cities, however, have ordinances that restrict the discharging of certain wastes with the water.

Acid Cleaning. Disposal of pickle liquors usually involves neutralization to prevent a chemical attack on concrete sewer structures or to prevent acidifying the receiving body of water. Also, it is often necessary to remove from the effluent the ferrous salts of the metal cleaned. Removal of the salts usually consists in precipitating them as a hydroxide. This is sufficient when the waste is discharged to a sewage system where simple sedimentation and incineration are employed as treatment procedures. However, in many localities these hydroxide sludges must be removed before the waste can be emptied into municipal sewer systems. This requires filtration and final disposal of the solids on dumps.

Supplements the articles on pages 299 to 301 of the 1948 ASM Metals Handbook

Water

The water rates for industrial users vary with cities from about $0.25 to $3.40 per 1000 cu ft. Thus, an operation costing $100 per month for water in one city might cost $1400 per month in another.

Whether the water is purchased from a municipality or is obtained from a private source of supply, the ultimate cost is determined by approximately the same factors—principally, pumping, purifying and amortization of equipment.

Water is used in metal cleaning processes as a coolant, as steam for heating, as the vehicle for the cleaning bath, and as the rinsing medium. Extreme purity is not usually required of water used for cleaning operations; the water generally available is sufficiently free from sediment, grease and excessive hardness. The water from relatively large lakes and rivers has these qualifications during normal periods. During periods of high turbulence, however, such water usually contains an excessive amount of suspended solids; coagulation, sedimentation and filtration are then required. Some well water can be used without treatment; some requires softening. Where extreme purity is necessary, processes such as ion exchange or distillation can be used; however, these raise the cost considerably.

Various measures to conserve water can be employed for conveyer-type cleaning installations. Since these units use large volumes of water, moderate reductions in flow will decrease the cost. Countercurrent rinsing systems are sometimes used. Sprays are substituted for flushing rinses and intermittent spray rinses are substituted for continuous spray rinses. (An intermittent rinse operates only when the parts are in the line of spray.)

Other Materials

The cost of cleaning agents other than water depends on the degree of

Table I. Approximate Relative Costs in Metal Cleaning

Typical cost relations for cleaning steel parts in large quantities[a]

Method	Direct Labor	Disposal Labor	Material	Water	Energy	Maintenance	Overhead[b]	Total of Columns to Left	Initial Cost of Equipment
Methods for Removal of Soil									
Vapor degreasing	5	2	9	0.1	2	0.5	2	20.6	50
Solvent cleaning (tank)	5	2	9	0	0.6	0.4	2	19.0	10
Alkaline cleaning									
Tank, hot	6	2	4	1	1	0.6	2	16.6	15
Spray, cold	5	2	3	0.9	0.1	0.6	2	13.6	40
Spray, hot	5	2	2	1.2	3	0.9	2	16.1	40
Electrolytic	6	2	4	1	2	0.5	2	17.5	70
Emulsion cleaning									
Tank, hot	5	2	3	1	2	0.6	2	15.6	15
Spray, hot	5	2	2	1.2	4	0.9	2	17.1	40
Methods for Removal of Scale									
Acid cleaning (sulfuric)	7	3	7	2.5	3.5	2	2	27.0	90
Abrasive cleaning									
Sand blast	6	2	7	0	3	8	2	28.0	100
Grit blast	6	1	8	0	3	9	2	29.0	100
Shot blast	6	1	8	0	3	9	2	29.0	100
Aluminum oxide	6	2	9	0	3	8	2	30.0	100
Salt bath descaling[c]	7	4	20	1	4	1	2	39.0	75

(a) Numbers in the first eight columns are on the same scale; numbers in the final column (initial cost of equipment) are on a scale of 100, for comparison in that column only, and have no relation to the scale used in other columns. (b) Overhead, shown as a nominal minimum, the same for all processes, will usually vary more with local conditions than the factors shown in the six columns to left. (c) Applies only to the cleaning of high-alloy ferrous material

cleanliness required, the quantity purchased, and the control of the operation. The material costs in Table I are based on cleaning the same number of parts by each of the cleaning methods and at reasonably high efficiency with low drag-out. These costs do not include materials for waste treatment or disposal.

Vapor Degreasing. The costs can vary over a wider range than for almost any other type of material. Pockets in the work, wind currents in the degreasing area, overloading and poor heating practices can waste considerable material. The material costs in Table I represent high operating efficiency.

Solvent Cleaning. The cost of these cleaning agents is usually less than for vapor degreasing. However, the solvent becomes contaminated and must be discarded or redistilled frequently. The drag-out or evaporation loss with this method of cleaning usually is high; therefore, the material costs are about as high as with any method of cleaning.

Hot Tank Alkaline Cleaning. Costs are usually low because the cleaning agents are relatively cheap and easily available sodium salts. Since a higher concentration of material is necessary in tank cleaning than in spray cleaning, more cleaner is lost through drag-out and direct disposal. For this reason the material costs will be higher than in spray cleaning.

Cold Spray Alkaline Cleaning. A liquid having high wetting characteristics is necessary in cold spraying because spray impingement without the help of heat is depended on to remove the soil. This requirement makes the spray material higher in cost than that for the hot spray method.

Hot Spray Alkaline Cleaning. Costs will usually be slightly less than for materials used in cold spray cleaning for the reason just mentioned. However, the cost may equal that of cold spraying when high cleanliness of work is demanded. The tendency of the bath to foam as contamination increases will accelerate the need for more frequent bath make-up.

Emulsion Cleaning, Tank and Spray. The cost of emulsions will vary depending on whether a special condition is met, such as the application of a rust-preventive oil during cleaning. In tank emulsion cleaning, material cost will be slightly higher than for spray emulsion cleaning because a slightly higher concentration is required.

Acid Cleaning requires acid, alkali for neutralizing after pickling, and usually a rust-preventive oil. Costs for these can vary considerably depending on the type of rust-preventive oil used or whether another acid (phosphoric or sulfamic) is used instead of sulfuric. The rating in Table I is for acid pickling such as used in a steel mill.

Abrasive Cleaning. Material cost in abrasive cleaning will vary with the smoothness of surface required, amount of grit or abrasive consumed, and whether an acid pickle will be used as a secondary operation.

Table II. Cost of Pickling

Figures are for a high-production operation on flat rolled steel 0.200 in. thick.

(Cost per ton based on monthly averages)

Item	Cost per Ton
Labor, inside	$0.692
Labor, outside (disposal)	0.332
Other labor costs	
Bonus, vacation, premium pay	0.008
Employee welfare fund	0.110
Materials	0.821
Energy and water	0.554
Maintenance	0.178
Overhead	
Factory	0.066
Office	0.044
Engineering	0.010
Insurance, taxes, depreciation	0.010
Other costs	
Tool charge	0.010
Freight and transportation	0.044
Miscellaneous	0.005
Total cost per ton	$2.884

Energy

The total cost for heating will depend on whether excess utilities are available or whether additional facilities are required. Heat losses can be high as a result of aeration of sprays and hot air drying.

Vapor Degreasing. Energy is needed to maintain the cleaning liquid at its boiling point (185 F).

Solvent Cleaning. Solvents are used at room temperature.

Alkaline Spray Cleaning. Heat energy is needed to maintain solution temperature at or above 180 F. Power is required for the pumps employed with spray equipment.

Alkaline Tank Cleaning. Tank operation requires the same heat energy as spray cleaning but no power, unless an agitator is used.

Electrolytic Cleaning. Heat is needed to maintain the solution at 180 F; electrical energy is required to provide about 50 amp per sq ft at 6 v direct current.

Emulsion Spray Cleaning. Heat energy maintains the solution between 160 and 180 F. Power is needed for pumps on spray equipment.

Tank Emulsion Cleaning requires the same heat energy as the preceding but no power unless an agitator is used.

Acid Cleaning (Phosphoric Acid). Heat energy is needed to maintain temperature between 160 and 180 F. Agitators are sometimes used.

Blast Cleaning. Air pressure at about 25 psi is used to propel the abrasive. Electrical energy moves the work.

Salt Bath Descaling. Heat energy is needed to provide temperature of 850 F.

Table III. Time Distribution for Two Cleaning Cycles

Cleaning Before Hard Chromium Plating

60 pieces per lot

4.1 hr total cleaning time per lot

Vapor degreasing	2.4% of total time
Acid pickling	18.3
Electrolytic cleaning	17.1
Vapor blasting	62.2
	100.0

Cleaning Before Bright Nickel Plating

13 pieces per lot

3.55 hr total cleaning time per lot

Vapor degreasing	4.2% of total time
Acid pickling	19.7
Electrolytic cleaning	18.3
Vapor blasting	57.8
	100.0

Maintenance

Maintenance of Solutions. For vapor degreasing, alkaline tank cleaning and alkaline electrolytic cleaning, this maintenance includes solution make-up, analysis and additions. Although a reasonable amount of caution is necessary in dissolving alkaline cleaners, a solution of 6 oz per gal can be made without danger about as fast as the material can be poured into the tank. Agitation and heat may be necessary to effect complete solution.

Alkaline cleaners should be analyzed daily for equivalent caustic, equivalent carbonate, difference between equivalent caustic and carbonate, and the sum of these two constituents. These analyses are especially important where a variety of metals are being processed. A double titration and the necessary computation will take about 5 min. Solvent is usually replenished each day on the basis of average usage, with small corrective additions as indicated by chemical analysis.

Degreasing solutions are purchased ready for use and can be pumped or poured directly into the machine. The analysis consists of a titration with acid for the pyridine-inhibited solvents, for example, permachlor, and a pH measurement for solvents containing neutral inhibitors. The presence of aluminum dust makes cleanout maintenance essential, since a "Friedel-Craft reaction" occurs to a slight extent even in the presence of inhibitors.

Acid cleaners can be analyzed by titration or by Baumé measurements of the specific gravity. The former is more accurate since dissolved metal salts will raise the Baumé readings. Make-up is usually from carboys, although acid buggies for larger installations are available with air pumps and hose.

Maintenance of Equipment. Maintenance of tanks and of the attendant piping constitutes the bulk of the maintenance work required in most cleaning installations.

Degreasers require cleaning of the still as well as the chambers through which the work passes. Since a degreaser may be heated by gas, electricity or steam, the nature of the maintenance will vary. Cooling coils and water jackets require little attention, but heating coils become caked with buffing and drawing compounds that must be removed about once each week.

Removing parts and sludge from spray or vapor chambers requires the labor of two men; the one working in the tank wears a respirator while the other watches from the outside to offer help in the event of mask failure or other accidents resulting from the trichlorethylene fumes.

Spray nozzles require periodic cleaning, even when screens are used as filters in the lines. Pumps, valves and packing suffer greater than normal wear, partly because of removal of lubricating oil and grease, and partly because of the wear by abrasives that are removed from the buffed and polished work.

Alkaline and electrolytic cleaner tanks must be cleaned periodically to remove scale and sludge. This interval may vary from a week to more than a month, depending on the work load and the kind and amount of soil removed. Frequent cleaning will minimize variation in quality of cleaning. Alkaline cleaning machines must be piped for steam, water and sometimes air if agitation is used. Drains (with overflows) or sewers connected to waste disposal facilities are usually lined with chemical-resistant tile. Valves and pumps that handle cleaners require more maintenance than those for water. Although pumps are not directly attacked by alkaline solutions, the removal of lubri-

Table IV. Pre-Plating Example — Cost of Energy and Materials

Computed on a monthly basis for cleaning 105,892 sq ft of steel parts in automatic machine before nickel plating

Energy (Electricity)		
Alkaline electrolytic cleaner for 126 sec total time at 23 amp per sq ft for 1000 sq in. = 0.03575 kwh		
$0.009 per kwh × 0.03575 =	$0.00032	
Cyanide cathodic cleaner for 48 sec total time at 17 amp per sq ft for 1000 sq in. = 0.01543 kwh		
$0.009 per kwh × 0.01543 =	0.00014	
Total cost of electricity	$0.00046	
$\frac{\$0.00046}{75\%\text{ efficiency}} =$		$0.00061
Energy (Steam)		
$\left(\frac{100\text{ lb per hr} \times 2\text{ tanks} \times 528\text{ hr}}{15{,}250\text{ thousand sq in.}}\right) \times \$1.50\text{ per 1000 lb} =$		$0.01038
Material		
Tank alkaline cleaner (7 stations)		
499 lb cleaner, $6.50 per 100 lb	$32.44	
320 lb sodium hydroxide, $4.00 per 100 lb	12.80	
3 lb wetting agent, $30 per 100 lb	0.90	
	46.14	
Electrolytic alkaline cleaner (4 stations)		
960 lb cleaner, $6.50 per 100 lb	62.40	
227 lb sodium hydroxide, $4.00 per 100 lb	9.08	
4 lb wetting agent, $30 per 100 lb	1.20	
	72.68	
Sodium cyanide electrolytic cleaner (2 stations)		
326 lb sodium cyanide, $18 per 100 lb	58.68	
	58.68	
Total cost of material	$177.50	
Cost per 1000 sq in. = $\frac{177.50}{15{,}250} =$		$0.01164
Water		
10 gal per min per rinse × 3 rinses × 21,120 hr = 633,600 gal per month.		
$\frac{633{,}600}{15{,}250} = 41.5$ gal per 1000 sq in.		
$0.90 per 1000 cu ft = $0.00012 per gal		
$0.00012 × 41.5 =		$0.00498
Total costs for energy and materials shown		$0.02761

Table V. Pre-Plating Example — Maintenance Costs

Solution Maintenance	
Replenishments, ½ hr per day	$21.00
Solution make-up, 3½ hr per month	7.00
Analysis, ¾ hr per day	33.00
Material handling, ½ hr per week	4.30
	$65.30
Cost per 1000 sq in	$0.00428
Equipment Maintenance	
Pipe fitting, material and labor	$10.00
Electrician's labor	10.70
Machinist's labor	23.50
	$44.20
Cost per 1000 sq in	$0.00289
Total cost of maintenance per 1000 sq in	$0.00717

Table VI. Pre-Plating Example — Initial Cost of Equipment

Tanks	
One 7-station, 2-lane alkaline tank	$ 540
One 4-station, 2-lane electrolytic tank	400
One 2-station, 2-lane electrolytic tank	240
Piping	
Estimated	700
Ventilation Equipment	
Blowers and vents (9 double ducts)	1,000
Heat Exchangers	
6 plate coils (5 by 2 ft) at $53.50	321
2 plate coils (2 by 2 ft) at $40.00	80
Generators	
One, 2500 amp, 9 v	5,000
One, 1500 amp, 9 v	3,000
Bus Bars	
100 ft by 2 by ½ in	203
Anodes	
24 perforated steel with double copper hooks	24
Installation Labor	
Tanks, piping and vents	2,000
Generators and bus bars	4,310
Total	$17,908

Table VII. Pre-Plating Example — Summary of Variable Costs

Direct Labor	(a)
Material	$0.01164
Water	0.00498
Energy	0.01099
Maintenance	0.00717
Total cost per 1000 sq in	$0.03478

(a) No direct labor is charged to the cleaners since all racking and unracking must be done for nickel plating.

Table VIII. Comparison of Cost for Vapor Degreasing and Alkaline Cleaning (Problem 1. Computed on an hourly basis)

Item	Vapor Degreasing			Alkaline Cleaning		
Variable Costs						
Direct labor		$1.75			$1.75	
Material		6.30(a)			2.16(b)	
Utilities						
Water, $0.05 per 1000 gal	$0.03(c)			.....		
Steam, $1.50 per 1000 lb	0.84(d)			.....		
Electricity, $0.03 per kwh	0.06(e)			$0.42(f)		
Gas, $0.40 per million Btu	.....			2.40(g)		
		0.93			2.82	
Maintenance						
Labor 7 × $2.00 per hr	0.35			0.50		
Parts	0.12			0.17		
		0.47			0.67	
Reject handling		....			0.80(h)	
Overhead, 25% of total labor		0.53			0.56	
Operating costs per hr			$ 9.98			$ 8.76
Fixed Costs						
Investment						
Building	0.27(i)			1.80(i)		
Equipment	0.90(j)			1.20(k)		
		1.17			3.00	
Depreciation		0.90(l)			0.60(m)	
Fixed costs per hr			$ 2.07			$ 3.60
Total costs per hr			$12.05			$12.36

(a) Trichlorethylene 11½¢ per lb; solvent loss 11 lb per ton. (b) Cleaner 18¢ per lb; loss 12 lb per operating hr. (c) 600 gal per hr. (d) 3000 million Btu (140 million to heat work, 100 million for spray, 70 million for cleaning spray, 120 million for outside still, 75 million for radiation). (e) 1-hp conveyer motor, 2-hp spray pump. (f) Two 7½-hp spray pumps, 1-hp conveyer motor, 3-hp blower. (g) Heating requirements for aeration and radiation losses in each spray tank (2 × 1000 million Btu) and 1000 million Btu to heat air in drier, or a total of 3000 million Btu. (h) For 2% rejects, which require stripping, recleaning and repainting at four times cleaning cost. (i) On basis of average construction of $1 per cu ft; 4% depreciation; gross return 12%, assuming 50% tax; upkeep and property tax; or, a total cost of $3.60 per sq ft per year. (j) Cost $9000; gross return 12%, assuming 50% tax. (k) Cost $12,000; gross return 20%, assuming 50% tax. (l) 20% per year. (m) 10% per year

Table IX. Summary of Cost Distribution for Vapor Degreasing and Alkaline Cleaning

Problem 1. Computed on an hourly basis (See Table VIII above.)

Item	Vapor Degreasing	Alkaline Cleaning
Labor, maintenance and overhead	22.8%	24.1%
Material	52.3	17.5
Utilities	7.7	22.8
Rejects	...	6.4
Investment and depreciation	17.2	29.2
	100.0	100.0

Table X. Summary of Cost Distribution for Vapor Degreasing and Emulsion Cleaning

Problem 2. Computed on an hourly basis (See Table XI below.)

Item	Vapor Degreasing	Emulsion Cleaning	
		Steam	Gas
Labor, maintenance and overhead	35.3%	31.9%	36.0%
Material	43.6	15.6	17.6
Utilities	5.3	25.0	15.3
Rejects	...	3.1	3.5
Investment and depreciation	15.8	24.4	27.6
	100.0	100.0	100.0

Table XI. Comparison of Cost for Vapor Degreasing and Emulsion Cleaning (Problem 2. Computed on an hourly basis)

Item	Vapor Degreasing			Emulsion Cleaning		
Variable Costs						
Direct labor		$1.75			$1.75	
Material		3.15(a)			1.30(b)	
Utilities						
Water, $0.05 per 1000 gal	$0.02(c)			...		
Steam, $1.50 per 1000 lb (90% efficiency)	0.30(d)			$1.83(d)		
Electricity, $0.03 per kwh	0.06(e)			0.25(f)		
Gas, $0.40 per million Btu (50% efficiency)	...			0.88(g)		
		0.38			2.08 (Steam) 1.13 (Gas)	
Maintenance						
Labor, 4 × $2.00 per hr per week	0.20			0.20		
Parts	0.10			0.20		
		0.30			0.40	
Reject handling		...			0.26(h)	
Overhead, 25% of total labor		0.50			0.50	
Operating costs per hr			$6.08		(Steam) (Gas)	$6.29 5.34
Fixed Costs						
Investment						
Building	0.18(i)			0.75(i)		
Equipment	0.55(j)			0.85(k)		
		0.73			1.60	
Depreciation		0.41(l)			0.43(m)	
Fixed costs per hr			$1.14			$2.03
Total costs per hr			$7.22		(Steam) (Gas)	$8.32 $7.37

(a) 2.25 gal per hr solvent loss. (b) Chemicals ($1.75 per gal) one gal per 19 gal water in 250 gal tank, overflow 6% per hr. (c) 400 gal per hr. (d) Degreasing: 183 million Btu (37 million for heating work, 30 million for spray, 30 million for condensate, 40 million for outside still, 46 million for radiation). Emulsion cleaning: 1100 million Btu (500 million Btu for total aeration and radiation losses in each spray tank, 600 million Btu for drier). (e) 1-hp conveyer motor; 1½-hp spray pump. (f) Two 4-hp spray pumps, 1-hp conveyer motor, 2-hp blower. (g) Heating requirements for aeration and radiation losses in each spray tank (2 × 250 million Btu) and 600 million Btu, or a total of 1100 Btu. (h) Require stripping and rehandling at four times cleaning cost. (i) On basis of average construction cost of $1 per cu ft; 4% depreciation; gross return 12%, assuming 50% tax; upkeep and property tax 2%; or, total cost of $3.60 per sq ft per year. (j) Cost $5500; gross return 20%, assuming 50% tax. (k) Cost $8500; gross return 20%, assuming 50% tax. (l) 15% per year. (m) 10% per year.

cating greases and oils increases the wear on bearing surfaces.

Bus-bar connections on electrolytic cleaners must be checked frequently for voltage drops. Maintenance of generators or rectifiers consists of brief inspection and lubrication; brushes and commutators require periodic cleaning, frequency of which varies inversely with the cleanliness of their surroundings. Exhaust hoods need cleaning from condensed cleaner fumes. If solution levels in the tanks get too high, foam and liquid are drawn up the stacks. Control valves for steam and automatic level controls for the cleaner need maintenance inspection each month.

Labor Time for Maintenance. The cost of labor for maintenance is relatively small in comparison with some of the other items, but it deserves consideration in a complete analysis of cost. Typical labor times, evaluated for normal conditions, and omitting lengthy shutdowns for major repairs, are about as follows: vapor degreasing, 8 hr per week; solvent, 1; tank alkaline, 4; spray alkaline, 8; electrolytic alkaline, 4; emulsion, 4; and acid pickling, 4.

Equipment

Vapor Degreasing. Heating coils are needed for the vaporizer, and water coils for condenser, redistillation unit and ventilating equipment.

Solvent Cleaning. The tank may be of cold rolled steel. No heating is required. Fume exhaust equipment (hood and ducts) is needed if chlorinated solvents are to be used.

Alkaline Cleaning. The tank may be of carbon steel. Hot tank cleaning requires steam coils and ventilating equipment. Cold spray cleaning requires pumps and piping (risers, headers and nozzles). Hot spray cleaning requires pumps and piping (risers, headers and nozzles), as well as steam coils and ventilating equipment. Electrolytic cleaning requires steam coils, ventilating equipment, bus bars and an electrical power source such as generators or rectifiers.

Emulsion Cleaning. The tank may be of carbon steel. Hot tank cleaning requires steam coils and ventilating equipment. Hot spray cleaning requires pumps and piping, steam coils and ventilating equipment.

Acid Cleaning. The tank should be lined with lead or other corrosion-resistant material, as well as the heating coils and ventilating units.

Cost Studies

Several examples of cost analysis given in the accompanying tables will illustrate the need for attention to all items of variable cost. Items of fixed cost are omitted in most of the tables.

Table II shows cost distribution for a particular pickling application, and Table III summarizes distribution of time for two cleaning cycles, each involving four methods in sequence.

Tables IV through VII pertain to cleaning in an automatic plating machine, before nickel plating; the operation is for a 16-hr day, 5 days per week.

Tables VIII through XII relate to comparisons of methods for specific jobs as follows:

Vapor degreasing versus alkaline cleaning
Vapor degreasing versus emulsion cleaning
Emulsion cleaning versus alkaline cleaning

The specific applications in these comparisons are as follows:

Problem 1 (Tables VIII and IX). Vapor degreasing compared with alkaline washing of cabinets made from 18-gage steel. Cabinets weigh 100 lb each. Work week is 40 hr, 2000 hr per yr.

Problem 2 (Tables X and XI). Vapor degreasing compared with emulsion cleaning of aluminum alloy reflectors weighing 4½ lb each. Work week is 40 hr, 2000 hr per yr.

Problem 3 (Table XII). Emulsion cleaning compared with alkaline cleaning of 52,800 gears per month, 100 per hr for a 24-hr day, 22 days per month.

Because of the specific character of these examples, the data are not applicable in general. In many applications selection of the method of cleaning is determined by the effectiveness of cleaning or by local conditions regarding availability of equipment in the plant, rather than by a comparison of costs. Hence, the examples included here are not recommendations for any particular method of cleaning.

Table XII. Comparison of Cost for Emulsion Cleaning and Alkaline Cleaning
Problem 3. Computed on a monthly basis of 528 hr

Item	Emulsion Cleaning			Alkaline Cleaning		
Variable Costs						
Direct labor, 528 (24 hr per day for 22 days) × $1.68 per hr		$887.04			$887.04	
Disposal labor, 1½ hr per week at $1.70 per hr		11.05			11.05	
Material		202.95(a)			11.49(b)	
Utilities						
Water, $0.035 per 1000 gal	$ 0.13(c)			$ 0.13(c)		
Steam, $0.49 per 1000 lb	8.59(d)			10.30(e)		
Electricity, $0.009 per kwh	30.14(f)			30.14(f)		
		38.86			40.57	
Maintenance						
Labor and material		82.13(g)			82.13(g)	
Operating cost per month			$1,222.03			$1,032.28
Fixed Costs						
Initial cost of equipment			$5,605.72(h)			$5,605.72(h)
Total cost per month			$6,827.75			$6,638.00
Total cost per hr			$ 12.93			$ 12.57

(a) 369 gal soluble oil at $0.55 per gal. (b) 191½ lb sodium orthosilicate at $0.06 per lb. (c) 795 gal per week for solution make-up, plus 10% per week for loss. (d) 660,000 Btu at 160 F (49.8 lb per hr for 16 hr per day). (e) 790,000 Btu at 180 F (60 lb per hr for 16 hr per day). (f) 7½-hp pump, 1-hp conveyer motor. (g) Includes labor for make-up, additions, analysis, handling, repair parts and labor. (h) Includes $5,095.04 for equipment and installation, $156.11 for wiring, $354.57 for pipe fitting

Health and Fire Hazards

Acids. Sulfuric, muriatic and phosphoric acids are dangerous to the skin. Sulfuric is a powerful dehydrating agent, which accounts for much of the "burning" and destructive action of this acid.

Muriatic acid gives off HCl gas which is immediately irritating when inhaled in concentrations of 5 ppm (parts per million) or more. Lower concentrations are apparently less harmful, but they may promote tooth decay.

Sulfuric and phosphoric acids are found in the air only when dispersed as a mist. Concentrations of sulfuric acid over 1 ppm may be intensely irritating to the upper respiratory passage.

Alkalies. Alkaline cleaners usually contain alkalies which are intensely irritating to the upper respiratory organs when dispersed as dust or mist. They are also strong skin irritants and especially damaging to the eyes. Data on permissible concentrations are not available.

Solvents. Paraffin hydrocarbons with boiling points from 104 to 212 F predominate in anesthetic action. As volatility decreases, irritating action becomes greater. Kerosene is not volatile enough to be an anesthesia hazard under most conditions but is primarily an irritant.

The fire hazard of volatile petroleum hydrocarbons is greater than the health hazard. However, gasoline vapor and air will not explode until the concentration exceeds 20,000 ppm (2%) but symptoms of narcosis may occur with 1000 ppm.

Carbon tetrachloride is one of the most harmful of the common solvents. Continued exposure to concentrations of 50 to 100 ppm will produce chronic effects such as nausea, loss of appetite and vomiting. Higher concentrations will cause jaundice. Severe and even fatal liver damage has occurred with exposure to concentrations between 100 and 200 ppm. The fatal cases have generally occurred when using it in fire fighting or from injudicious use of this solvent in a confined space. Maximum allowable concentration is 30 ppm. H. B. Elkins states: "Alcoholism predisposes to carbon tetrachloride poisoning."

Trichloroethylene has relatively slight toxic effect as compared with carbon tetrachloride but maintenance men have lost their lives climbing inside tanks containing very high concentrations of trichloroethylene vapors. Death was attributed to the strong narcotic power. A maximum allowable concentration of 190 ppm is recommended.

Tetrachloroethylene, sometimes called perchloroethylene, is a strong narcotic with little other toxic effect.

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Creep and Creep-Rupture Tests

By the ASM Committee on Creep

CREEP may be defined as plastic strain occurring under constant or nearly constant stress. All metals creep at a sufficiently high temperature, which varies with the metal. Thus lead may creep at room temperature, whereas a metal such as molybdenum might not creep a like amount even at temperatures to 1500 F.

The rate of creep (that is, the slope of the curve of creep strain versus time) in a specific material depends on the temperature, the imposed stress and the time. Whereas, at relatively low stress and temperature, creep may stop, at high temperature it generally will continue until the metal breaks. Hence, design must be based on an anticipated useful life that depends on the application. For example, a guided missile might be designed for one hour, whereas central station power generating equipment may be designed for a life of 20 yr or more.

Whatever the application, the stress applied in a creep test must be such that fracture does not occur, and in many instances it is also necessary that the strain should not exceed a limiting amount; for example, 1% in steam turbine and piping applications. The data that the designer requires for selecting working stresses within these restrictions are provided by creep and creep-rupture (also called stress-rupture) tests, and, if dynamic stressing is involved, by fatigue tests. Short-time tension tests at elevated temperature—even those in which the strain-rate is held constant—are of little value for selection of working stresses, except possibly in applications involving an operating life of short duration.

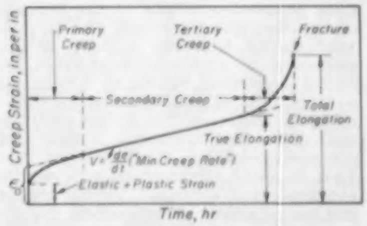

Fig. 1. Typical Creep Curve Defining Various Portions of the Curve

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ASM-SLA Q3

Both creep and creep-rupture tests are conducted conventionally by applying a constant load to a test specimen held at constant temperature. If the specimen fractures during test, it is termed a creep-rupture test, whereas if the test is discontinued before rupture, it is termed a creep test. Creep strains, as a function of time, are always measured in the creep test, but, even though desirable, not always in the creep-rupture test. A series of such tests at different loads, at each temperature of interest, provides the basic information from which can be evaluated the dependence of creep strain and fracture on stress, time and temperature, as discussed below.

Supersedes the article on page 115 of the 1948 ASM Metals Handbook

Since the cross-sectional area of a specimen undergoing creep is continuously changing, it is to be recognized that with constant applied load, the stress does not remain constant. However, since the magnitude of creep strains that may be encountered in service is usually quite limited, the change in stress during the test is often unimportant. When the change in stress is of important magnitude, or when interest centers on the fundamental aspects of creep phenomena, constant-stress tests may be made, and several ingenious techniques for maintaining constant stress are available.

A typical curve of creep strain versus time, in a constant-load tensile creep test (Fig. 1) is conveniently broken into four parts: (1) the elastic and plastic deformations that occur on application of the load (the elastic and plastic strain on loading are difficult to differentiate; the simplest way is by an independent measurement of modulus of elasticity, which permits a separate evaluation of the elastic strain); (2) a period of primary (transient) creep in which the rate of creep diminishes with time; (3) a period of secondary creep in which the rate is virtually constant (steady state or minimum creep rate); (4) a period of tertiary (third stage) creep, or accelerating creep rate, which ends in fracture.

Figure 2 shows the variation in creep rate as a function of time, as determined from Fig. 1. It will be noted that steady state creep is not in fact steady

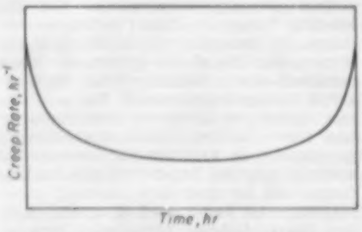

Fig. 2. Creep Rates During Various Periods of the Creep Test

but goes through a minimum. For practical purposes, however, an average value of the creep rate in the secondary period is conveniently defined as a region of "minimum creep rate".

Under special conditions certain of the stages may be accentuated or even absent; thus, at relatively high temperature the creep curve may appear to show an accelerating rate from the outset, whereas in relatively brittle metal the tertiary stage may be absent for practical considerations. In some alloys, microstructural changes occurring during test may cause departures from typical behavior.

Whereas creep, in the popular conception, becomes evident as a change in length with time (Fig. 1) it may also manifest itself in a reduction in stress while maintaining a constant length, as in bolting. In such applications, the elastic strain initially imposed on a bolt is replaced by creep strain, while the over-all length remains fixed, with a consequent reduction in hold-down stress. This manifestation of creep is termed "relaxation" and is studied in "relaxation" creep tests which, in general, simulate the behavior of a bolt.

In selecting working stresses for equipment operating under static conditions at elevated temperatures, information concerning time to rupture (creep-rupture tests) is always needed, even though it may not be the determinant factor. In other equipment where the amount of strain that can be tolerated is a limiting factor, creep-strain data are also needed and often prove determinant in setting allowable stresses. Thus, it is quite fallacious to think of the substitution of time-for-rupture data for creep-strain test data, or vice versa.

Specific recommendations regarding the length of time that creep and rupture tests should be conducted cannot be made without reference to the anticipated service life. For relatively short-life applications, such as guided missiles or jet engine applications, it is common to conduct tests lasting as long as the contemplated service. For longer-life applications, as in central station power generation, it is manifestly impossible to test for as long as 20 to 40 yr, and extrapolation of test data is necessary. For such applications, the longer the test, the more confident the extrapolation, and whereas no hard and fast recommendation can be made, many tests in reference to such applications now continue as long as 10,000 hr (417 days). Also, metals may be exposed for long periods without stress at elevated temperature and then creep tested in the conventional manner.

Creep Testing Machines and Grips

The primary requirement for the loading frame is either to impose (1) constant force or (2) constant stress during the life of the specimen. Since constant-stress testing (with load altered during test to match the continuous change in specimen cross section) has thus far been used for research purposes only and not for commercial testing, only the constant-force loading frame will be described here.

Creep has been studied under various types of stress, principally tension, compression, bending and torsion. In some problems the state of combined stress becomes important, and creep tests have been conducted under internal pressure and combinations of torsion and tension. Also creep has been investigated under cyclic temperature and cyclic stress. Of these only the tensile creep test at constant temperature has attained general acceptance for commercial testing and will therefore be the only type of test described here.

ASM Committee on Creep

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Recommended practices for creep testing have been published (see ASTM E22-41, for example) to guide investigators. However, many variables are not yet clearly understood in creep testing, and fixing all testing details rigidly might prove detrimental to the best interest of progressive research. Consequently, no attempt has been made in the ASTM recommended practices to prescribe specific and detailed procedures and apparatus. Rather, attempts are made to cover only the principal variables, such as temperature, stress, time and extension, which are known to be important. Since other variables, such as specimen shape and the surrounding atmosphere, might also be of great significance, current recommended practices should be considered advisory, rather than restrictive.

Most recommended practices for constant-load creep tests specify that the load on the specimen should be known with an accuracy of 1%. The load on the specimen during its entire life should be maintained within 1% of its original value. Thus, some types of machines may require readjustment during a test so as to maintain constant load, particularly if creep is extensive.

Various schemes for applying and maintaining constant load have been used; three will be discussed.

The simplest by far is direct loading without the use of beams. However, because of the wide range of stresses studied for any one metal, greater flexibility of stress application is possible through beam systems. Where the stress is low, direct loading is feasible and involves the least danger of error.

In most machines the load is applied by means of dead weight operating through a lever having an amplification from approximately 5 to 20. In high-capacity machines, double levers have been used to obtain a higher amplification so that excessive weights are not required. In general, the minimum practicable amplification should be used and other design precautions should be observed so that errors caused by incorrect location or wear of knife edges or other lever pivots do not affect lever alignment and ratios within the 1% mentioned above. Also the number of readjustments required to avoid excessive lever displacement and to maintain constant force during extensive creep decreases with decreasing lever ratio. As in all dead-weight types of machines, special precautions should be taken to insure smooth application of load, since even temporary overloading may affect the results of the test for some metals.

In a third type of machine, in which mechanical or hydraulic loading is used, a calibrated elastic member or spring dynamometer is placed in series with the specimen to indicate the load so that dead weight is not required. Since creep in the specimen may significantly relax the load on the dynamometer, this type of loading frame generally requires a follow-up system to maintain constant deflection, and thus constant force, in the dynamometer.

In some installations a multiple test setup has been used so that as many as 48 test specimens may be loaded in a large common furnace, each specimen having an independent loading system supported by a common frame.

Since the shock and vibration caused by fracture of a specimen in a multiple test setup or in an adjacent loading frame or by nearby equipment may affect the test results, special frame mounts are sometimes necessary for insulation against vibration.

Whatever type of loading frame is used, careful attention should be given to the method of attaching the grips and to the concentricity of specimen loading. Unless the resultant load passes through the center of the test section, serious variation in stress distribution may occur, particularly during the early part of a test when bending of the specimen is more probable. Thus, spherical heads, crossed knife-edges, or universal joints are generally used to improve alignment of grips. In general, such pivots or swivels must have low friction to be effective. In addition to this, the threads in the specimen grips must be concentric with the pivot line; otherwise, serious bending might result.

Threaded ends are most common for grip attachment; an adequate number of threads must be provided for gripping to avoid upsetting of the threads of the specimen or holder and to prevent thread fracture. A tight fitting grip is to be avoided. In addition, on round specimens spherical seating or a taper seat is sometimes used, especially for materials that do not machine well. For sheet specimens a hole and pin arrangement is most common. Efforts to avoid specimen-to-grip seizure are important, especially for the higher test temperatures. Preoxidation, graphite dipping and refractory washes are sometimes used to minimize welding-in. In general, it is desirable to check experimentally the stress distribution in the specimen so that the variation from the average stress is less than 5%.

The Test Specimen

Above all, to have significance, the test specimen must be representative of the alloy and structure. In the preparation of the specimen every effort must be made not to introduce side effects. The three important factors in the design of a test specimen are: (1) form of the end connection and reduction from ends to test section; (2) the gage length; and (3) the size and form of the cross section.

In deciding on the form of the end connection, it is necessary to consider not only strength factors, but also the effect of specimen ends on the uniformity of stress distribution in the test section. The reduction from the ends to the test section should be gradual (minimum fillet radius should be approximately equal to the specimen radius) so that serious concentration of stresses and local stress fields are not produced. Although the stress concentration may not seriously weaken many specimens under static loading, it might cause a local stress field within the gage length of the specimen and thus affect creep measurements. However, if the length of the test section beyond the gage length is reasonably great (for example, one radius) and if gage length is a minimum of about 4 diam. significant error in measurement of strain will not result because of end restraint. For creep-rupture tests of ductile metals where the strains are measured from the shoulders, the fillet radius can be made small (½ the specimen radius) to provide an effective gage length of greater stability.

The selection of an appropriate gage length is a compromise between two factors. A longer gage length generally enables greater sensitivity of measurement of unit creep values; however, because of the necessity for uniform distribution of temperature over the gage length, the longer gage length imposes much greater difficulties in temperature control. Furthermore, specimens with a long gage length are more difficult to make. Although gage lengths up to 10 in. have been used, the 2-in. gage length is usually employed. (A 1-in. gage length is also used for creep-rupture tests involving small strains, especially in testing alloys for aircraft gas turbines.) The dimension of the test section should be uniform throughout the gage length; a tolerance of ±0.5% is suggested by the ASTM recommended practice.

The two most common forms of specimens used for creep tests are cylindrical and flat; the cylindrical specimen is preferred from the test viewpoint if there is a choice. Most circular cross sections fall in the range from 0.160 to 0.505-in. diam. Here, too, the specimens with smaller diameter permit simpler loading and furnace construction and control; however, the contribution of small defects such as inclusions or segregation or the variations caused by grain size are best averaged out in the larger cross sections. Very few data are available on the effect of shape of the specimen cross section. In alloys where oxidation or decarburization or intergranular corrosion occurs, the diameter of the specimen becomes an important factor. Also, under creep strains, the shape of the cross section may affect the nonuniformity of strain and thus may alter the observed gross behavior within the gage length.

If the creep is measured over the entire specimen, it becomes important to consider creep in the fillets. Since the gage-length equivalent of the fillets is not constant but may vary with temperature, stress and time, the equivalent gage lengths for both the elastic and the plastic components of the strain should be carefully determined.

In preparing the test section of a specimen, it is necessary to consider not only surface smoothness, but also the distortion, cold working, and residual stress caused by the machining operation. During final cuts, only a small amount of metal should be removed, in order to minimize surface effects, but the cut should be deep enough to avoid smearing the metal.

Measurement and Control of Temperature

Accurate control of temperature is demanded in the determination of the creep properties of metals, and in ASTM Recommended Practice E22-41. Appreciation of the importance of this test variable has been the major factor contributing to the ability of various laboratories to obtain creep results reproducible by other laboratories. Not only is creep behavior highly sensitive to temperature, but often the magnitude of creep increments being measured is in error because of similarity to thermal expansion changes caused by temperature fluctuation.

The attainment of constant and uniform thermal conditions over the specimen gage length requires an appropriate heating source, temperature - measuring element, and control device best suited for the type of specimen, environment, and range of temperature under consideration. The most common form of heating furnace adopted for general creep testing has been the wire-wound resistance type consisting of a nichrome, kanthal, or platinum-rhodium wire wound on a refractory core of tubular shape contained within an insulated casing.

By proportioning the spacing of windings, rough compensation may be made for heat losses from the furnace ends and openings. A finer adjustment of temperature gradients over the specimen gage length may be accomplished by tapped connections on the windings, which permit shunting of appropriate sections by external resistors. Figure 3 illustrates the arrangement of such a winding for a furnace requiring a window opening for optical measurements of creep. The closer winding at the ends compensate for heat losses from the furnace ends and the conduction of heat from the furnace through the rods that hold the specimen.

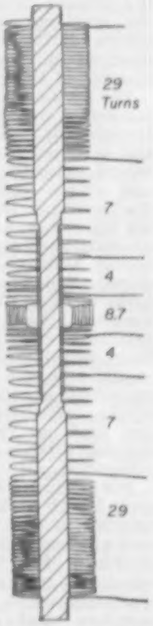

Fig. 3. Wiring Arrangement for a 12-In. Test Furnace with a Window, Showing the Number of Turns, with Provision for Local Adjustment of Temperature (J. A. Fellows, E. Cook and H. S. Avery, Trans AIME, 150, 360, 1952)

An alternative winding arrangement may consist of separate coils of wire over several sections of the furnace to which the power input may be regulated individually. A metallic sleeve of good thermal conductivity, located on the inner side of the furnace core, is sometimes used where conditions permit, for further minimizing temperature gradients.

Where relatively rapid heating rates or extreme temperatures are required, the test specimen may be heated by passing heavy current through it. Where such a heating method is used, temperature of the specimen must be measured carefully, because of the sharp transverse temperature gradients existing in the medium surrounding the specimen. This method of heating would not be used where large deformation of the specimen or nonuniform elongation would be expected because of localized hot spots.

Molten salt or oil baths are used advantageously in some instances. While excellent distribution of temperature and rapid heating conditions result, other experimental difficulties may be encountered or undesirable surface reactions may develop between specimen and environment.

Temperature of the specimen can be measured and controlled most conveniently and with reasonable precision by means of thermocouples in conjunction with potentiometric-type indicating and automatic-controlling instruments. In spite of the 1 or 2 F sensitivity of the commercially available potentiometric temperature controllers of either the galvanometer or electronic-detection type, various precautions must be taken in the external control circuitry to minimize cycling of temperature. This situation can be helped by (1) locating the control thermocouple near the furnace windings; (2) selecting appropriate power input by means of a variable transformer; (3) throttling power over a high-low range rather than on-off; (4) utilizing proportionate controlling devices or anticipatory circuits. A typical temperature control circuit is shown in Fig. 4.

Other forms of temperature-control elements, such as resistance thermometers or thermal expansion systems, have been used satisfactorily for creep testing.

In addition to the need for automatic control of temperature, acceptable creep-testing practice requires that the gage-length temperature of the specimen be monitored throughout the duration of the test both by automatic recording and by manual checking with a precision instrument. It has been found feasible to maintain indicated test temperatures within 2 or 3 F of the nominal value over prolonged periods of time, with thermocouple systems where precautions have been taken to hold room temperature constant and to regulate the line voltage. The absolute tempera-

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ture value may, however, be no better than ±3 to 5 F unless extreme precautions are taken.

The accuracy with which the indicated temperature represents the actual temperature of the specimen will depend on the type of thermocouple used, the care taken in the attachment of thermocouples to the specimen, the initial calibration, and the extent of calibration change during the test because of environmental conditions. Contamination or deterioration of thermocouples in long-time tests and at high temperatures is also an important consideration.

Measurement of Strain

In creep testing, extensions of the order of 0.001 to 0.00001% per hr must be measured accurately. In creep-rupture testing, even though strain measurements are sometimes omitted, it is desirable to measure elongations of the order of 0.001 in. accurately.

A number of methods are available for making accurate measurements. They are of two types: (1) those that are read outside the furnace, primarily through extension rods attached to the specimen and used to activate an external strain-measuring system; and (2) those that are read optically inside the furnace from strain gages attached to the specimen.

One of the more sensitive methods of the first type was developed by Martens. Two parallel arms are attached to the specimen and extend out of the furnace. A rhomb supporting a small mirror is attached in V-notches between the two arms by means of light springs. Relative movement of the two arms rotates the rhomb and mirror. The deflection caused by the strain is measured by sighting through a telescope the reflected image on a scale a measured distance away from the mirror.

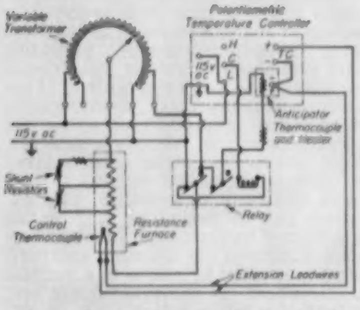

Fig. 4. Typical Temperature Control Circuit for Creep Testing

Similarly, the use of two parallel arms extending outside the furnace permits the attachment of a sensitive dial gage, or a set of SR-4 strain gages that permit direct reading in the first instance and automatic recording in the second, or a linear differential transformer that is capable of detecting small changes in strain with a high degree of accuracy and also permits automatic recording of creep. Such an extensometer system is illustrated in Fig. 5.

With the SR-4 strain gages, the extension arms contact cantilever beams to which the gages are attached on both the tension and compression sides. The gages on each pair of beams are electrically opposed so that the net change in resistance caused by beam deflection induced by specimen elongation is added electrically to give a reading proportional to the average extension of the specimen.

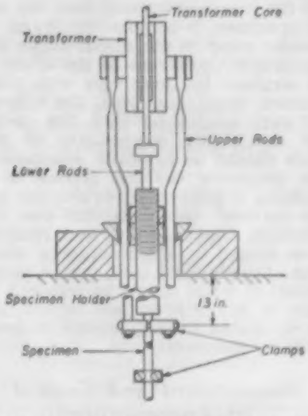

Fig. 5. Extensometer System Using Linear Differential Transformer To Detect Small Changes in Strain

In any system using extension rods attached to the specimen and extending outside the furnace, the accuracy of the reading depends on: (1) room-temperature control and similar exposure of both rods to temperature changes; (2) place of attachment of the rods to the specimen. (Attachment at the shoulder obviously requires a correction for creep outside the gage length. Attachment at the gage length is a problem because of the notching of the specimen and the slippage that occurs during creep as a result of changes in specimen diameter); (3) stability of the extension rods.

The second class of methods for measuring requires a window in the furnace through which the specimen and attached gage markers can be observed optically, usually at 100 diam and with a long working distance for the telescope. If a double window is used (one at each gage mark), a double telescope is required, which uses an invar block to avoid dimensional changes. Fine platinum wires are either attached at the shoulder or spot welded or wired at the gage marks. Fine notches are used as reference markers to measure elongation.

For specimens of short gage length, it is much simpler to use a tube and wire combination as shown in Fig. 6. The wires and tube may be platinum or a stable stainless steel or nichrome. Only one window is required and therefore one telescope for reading. Fine notches in the wire, using the top of the tube as a reference point, permit accurate readings of strain.

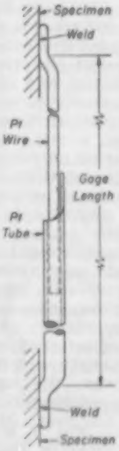

Fig. 6. Wire and Tube Optical Method for Measuring Creep (N. J. Grant, in "High Temperature Properties of Metals", ASM, 45, 1951)

There are both advantages and disadvantages in these different methods. The optical method is independent of changes in room temperature (the Martens method requires ±1 F for accurate work) provided the furnace and control system are operating adequately. Attachment at the gage points is simpler with the optical method and permits a more accurate "zero" reading. Unfortunately the furnace is more difficult to build for accurate temperature distribution and control when a window must be included.

For creep-rupture work, where accurate strain readings are not critical, a dial gage capable of being read to the nearest thousandth of an inch is frequently adequate to establish a strain-time curve by measuring between two points outside the furnace, provided the grip system is so sturdy that measurable creep is not taking place. A true zero is not obtained for the curve, but the minimum requirements of a curve are met. A similar approximate curve can be obtained by measuring the drop of the beam used to apply the load. The magnification obtained by the beam provides a reasonably good curve subject to the same limitations as the dial method.

Reporting of Data

Selection of materials and allowable stresses for use at high temperature is based on the requirement that no part become inoperative because of creep. All designs require that failure must not occur by creep-rupture within the design life. Usually, however, limited deformation in the required life is the design criterion. Most designs limit deformation to no more than 1% and some require as little as 0.1%.

Creep and rupture properties are influenced by all the metallurgical variables to which the metal is exposed during manufacture and fabrication. Reporting of data should, therefore, include the chemical composition, type and size of melting furnace, whether tested as a casting or a wrought product, size and form of material, and heat treatment or other procedures for final conditioning. In addition, data are useful by which the response to earlier history can be judged, such as hardness and mechanical properties at room temperature, grain size and microstructures. Any other information pertinent to general applicability of the data, such as type of deoxidation of steels, is helpful in evaluating data.

In collecting and correlating available information on the properties of alloys at high temperatures, the Data and Publications Panel of the ASME-ASTM Joint Committee on the Effect of Temperature on the Properties of Metals has developed efficient forms covering the minimum desirable data.

Rupture Data. Basic data from rupture tests are the stress and rupture times together with elongation and reduction of area. Usually, the data concerning stress-rupture time are presented as log-log curves (Fig. 7). It is common practice to conduct tests with fracture occurring at about 1000 hr in establishing such curves, although the data are more valuable if tests of longer duration are made. Stresses for rupture

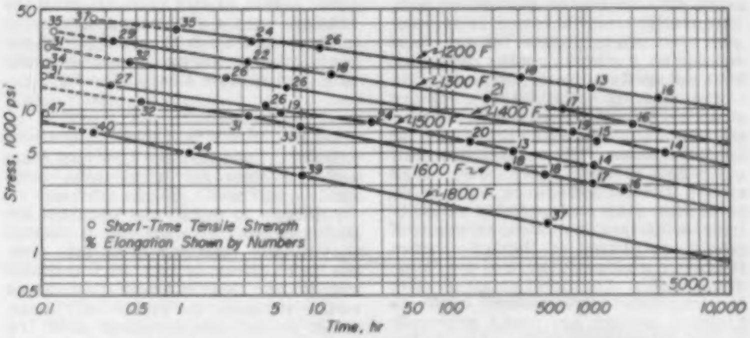

Fig. 7. Curves of Stress Versus Rupture Time for 18-8 Stainless Steel

in definite time periods can be read from the curves, with those for rupture in 10, 100 and 1000 hr most commonly reported. The actual test data are frequently omitted in reports, even though they are desirable for many purposes.

When the curves show no breaks over the range of test values, the usual straight-line stress-rupture time curves are extrapolated to 10,000 and 100,000 hr to establish stresses for rupture at these time periods. When rupture strengths are available over a range of temperatures, it is customary to show curves of rupture strength versus temperature, for specific rupture life values (Fig. 8).

Values for Elongation and reduction of area are usually reported only with the actual test data. It is desirable to note both values on the stress-rupture time curves, although usual practice is to show only elongation (Fig. 7). Interpolated values are frequently included with tabulations of rupture strengths.

Design Curves. When creep data are taken during rupture tests, it is most convenient to plot curves showing times for various total deformations (elastic plus plastic on loading, as well as time-dependent creep) for the test stresses (Fig. 9). Supplementing the rupture tests, lower-stress creep tests enable plotting of such curves for 0.1, 0.2, 0.5 and 1% deformation and in some specimens larger amounts. Such presentations, first developed by M. J. Manjoine (Trans ASME, 67, 111, 1945), have been termed "design curves" inasmuch as the designer can select the design stress directly from the curves at each temperature if the strain tolerable during service life is known.

Design curves are usually plotted as stress versus the log of time. This is merely a convenient form and has no fundamental significance. No method is known for extrapolating such curves directly and reliably; consequently, they are usually limited to the actual maximum testing periods.

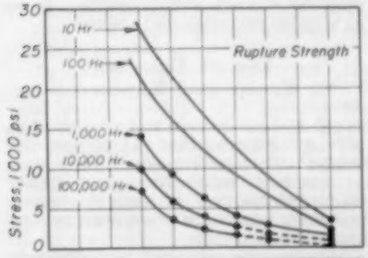

Fig. 8. Summary of High-Temperature Characteristics of 18-8 Type Stainless Steel

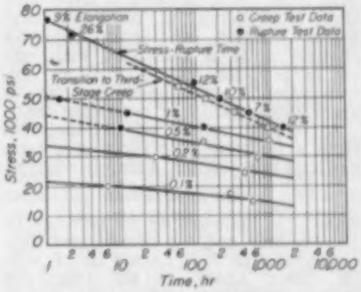

Fig. 9. Design Data for Low-Carbon N-155 Forged Alloy Disk Tested at 1200 F (N. J. Grant and A. G. Bucklin, Trans ASM, 42, 720, 1950)

Creep Strength Data. Stresses for limited deformations in prolonged time periods are usually reported in this country as creep strengths. These strengths are normally derived from tests of no more than 1000 to 2000-hr duration by plotting stress against secondary creep rates on logarithmic coordinates, with three or four tests in the range of 0.0001 to 0.00001% per hr (Fig. 10). The secondary rate is either the true minimum creep rate or an approximation of this from an average rate over the last few hundred hours of testing, and as such does not represent the same "minimum".

For many years it has been customary in this country to evaluate materials in terms of the stresses for creep rates of 0.0001 and 0.00001% per hr and to treat them as equivalent to the following amounts of creep at longer time periods by simple multiplication:

% per hr	% per 1000 hr	% per 10,000 hr	% per 100,000 hr
0.0001	0.1	1.0	...
0.00001	0.01	0.1	1.0

Creep strengths are most often reported in terms of the stresses for rates of 0.1 and 0.01% per 1000 hr (Fig. 8).

A reported creep strength can be used to calculate actual deformations only when the creep rate remains unchanged over the period of extrapolation, or at least represents an average value for that period. In addition, correction should be made for deformation during loading and during primary creep. A convenient method of obtaining such data is to determine the intercept, ϵ_o (Fig. 1) of the extension of the straight-line secondary creep asymptote to the creep curve back to the strain axis. Total extension ϵ at time t is:

$$\epsilon = \epsilon_o + vt$$

when v is the secondary creep rate. Inclusion of intercept values in reports is, therefore, highly desirable.

The amount of deformation and the duration of primary, secondary and tertiary creep are rarely specifically reported in engineering data. There are, however, many instances where careful attention should be given to these characteristics. Sometimes the design curves show the start of secondary or tertiary creep. This indicates the stress-time relationships for onset of rapidly increasing creep in the tertiary stage.

Plotting of Curves. Most stress-rupture and stress-creep rate curves are plotted on logarithmic coordinates. Sometimes, however, semi-log plots of stress versus the logarithm of the rupture time or creep rate are published, since many theoretical treatments require a semi-log plot. In certain instances, the data are represented equally well either way. Probably neither method is wholly correct, and the actual relationships involve hyperbolic sine curves. Either log-log or semi-log plots give good approximations of this curve at high and intermediate stresses.

Changes in the slope of log-log curves using the convention of plotting straight-line segments also emphasize or maximize instabilities of structure or surface during testing, and signal changes in mode of creep or fracture that may be important to interpretation.

Complete reporting of the creep and rupture properties of an alloy would require design curves from actual data extending to at least 1000 hr for a number of temperatures in the useful temperature range of the alloy, supplemented by creep data for extrapolating deformation curves. The time and expense for such a complete evaluation, however, usually restricts testing to only a portion of the complete range. Most testing provides data for specific applications or for surveying properties. It is important to recognize that such limited tests provide only part of the deformation dependency on stress, time and temperature, and that the relative strengths can vary with stress, time and temperature.

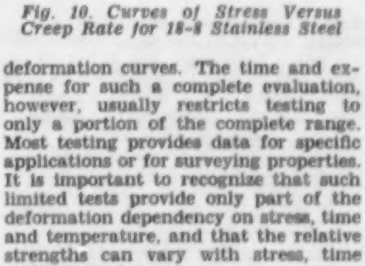

Fig. 10. Curves of Stress Versus Creep Rate for 18-8 Stainless Steel

Additional Desirable Data. Besides creep and rupture data, it is often desirable to report results of tensile, impact and hardness tests after exposure to creep conditions. Structural changes in the metal, or surface corrosion may alter physical properties drastically and induce susceptibility to shock loads and stress concentrations, particularly during shutdowns and restarts where thermal stresses can be severe.

Extrapolation of Data

Absolutely reliable extrapolation of rupture curves to prolonged times requires the absence of changes in slope in the log stress versus log rupture life or creep-rate plots. This seldom happens and one must utilize data that clearly indicate changes in structure. For this purpose, stress-rupture time curves for several temperatures lends confidence to extrapolation.

Changes in structure leading to changes in slope usually occur sooner as the temperature increases. Thus, if there are no marked differences in slope for curves over a range of temperatures of possibly 200 F or more for time periods as long as 1000 hr, extrapolation as a straight line of the lower-temperature curve to 10,000 hr is quite safe, and may even be safe to 100,000 hr.

Marked differences in slope for curves within about a 200 F interval are a sure indication of a change in slope of the lower-temperature curve over the time period of extrapolation, indicating the need for longer tests or careful approximations of the probable influence of the change in slope. Such changes in slope are almost always toward lower stresses for rupture in a given time period. Only rarely is a flattening off to higher stresses observed. Titanium, tested above about 1000 F in air, shows this effect, from alloying of oxygen absorbed from the air.

Rupture Strengths should be considerably higher than creep strengths if the extrapolation of secondary creep rates for limited deformations is to be trusted. If creep strengths are nearly equal to the rupture strength, or higher, as is frequently observed, either rupture will occur with low deformation or tertiary creep will start prematurely and cause more creep than predicted from the secondary creep rate. Since extrapolated rupture strengths on log-log plots are never low, a high ratio of creep strength to rupture strength should be viewed as questionable.

Assuming reliable rupture data, low ratios of creep to rupture strength are almost always indicative of continued decrease in creep rates with time to values below those established in the creep tests. Ratios of creep to rupture strength of the following order indicate reliable creep data for extrapolation:

$$\frac{0.0001\% \text{ per hr creep strength}}{10{,}000 \text{ hr rupture strength}} = 0.7 \text{ to } 0.8$$

$$\frac{0.00001\% \text{ per hr creep strength}}{100{,}000 \text{ hr rupture strength}} = 0.4 \text{ to } 0.6$$

Because of structural instabilities, deviations from the ideal type of creep curve are common. Primary creep may be virtually absent or may be excessive and extend over prolonged periods of time. Secondary creep may persist for only very short time periods because of tertiary creep. For the more brittle materials tertiary creep may be largely or entirely absent. Such factors point to the desirability of checking extrapolation for limited deformations from creep data by means of rupture tests. Frequently, creep behavior is so complex that rupture data are far more reliable for design unless the creep tests that are used approach the service life.

The log-log relationship between stress and minimum creep rate is usually not a single straight line over wide ranges of stress. The curve is generally quite flat at high creep rates (high stress) with an increase in slope at intermediate rates and probably a further increase at very low rates, especially if points are plotted at the low stresses that are not representative of the "minimum" rates. The usual range of rates for long-time extrapolation, 0.0001 to 0.00001% per hr, are found ordinarily in the intermediate slope. After studying available data, P. G. McVetty (Mech Engineering, March 1934) found that most data favored a hyperbolic sine relationship, a condition that would explain the usual apparent changes in slope associated with log-log or semi-log plots. Therefore, extrapolation of stress-creep rate data to lower rates should be done cautiously.

A reliable means of extrapolation from a few relatively short-time tests has long been sought. A simple relation,

$$T\,(20 + \log t) = K$$

when T is the absolute temperature in deg Rankine and t is the rupture time as proposed by F. R. Larson and J. Miller (Trans ASME, 74, 865, 1952), fits rupture data remarkably well for a fairly large number of metals. Apparently it can be adapted to creep data with considerable success. It offers an opportunity for evaluating the approximate strength of an alloy or for comparing the effect of metallurgical or processing variables through a few short-time tests.

A test of 12 hr at 1350 F has the same parameter value, K, as a 1000-hr test at 1200 F, if the constant is 20. For most metals, the correlation is not accurate enough for the strengths to be relied upon generally to more than about ±10%. The utility improves with the number of points over a wide range of testing conditions, especially if such points permit the selection of a constant more representative than 20.

The relationship has been used increasingly and has been adopted in the most recent ASTM compilation of properties of metals at elevated temperatures (ASTM Spec Pub 160, 1954). Extreme caution is required in its use for extrapolation to longer time periods.

A time-temperature relationship has also been proposed by S. S. Manson and A. M. Haferd (NACA Tech Note 2890, March 1953) for the extrapolation of creep and stress rupture data:

$$(T - T_a)/(\log t - \log t_a) = K$$

where T is the temperature in deg F and t is the rupture time in hours, and T_a and $\log t_a$ are material constants that can be determined by rupture data in the time range from 30 to 300 hr. A plot of this parameter against stress appears to result in considerably less scatter than was observed by the Larson and Miller method that utilized fewer and shorter tests. T_a and $\log t_a$ are both, of course, determined experimentally, and require more data than the Larson and Miller method; therefore they are considerably more accurate than the rather arbitrary Larson-Miller constant of 20.

Later Manson and W. F. Brown, Jr. (Proc ASTM, 53, 693, 1953) extended the relations with a generalized correlation method that leads to a suggested explicit relation among stress, temperature, and rupture time in the form

$$(T - T_a)(\log t - \log t_a)^{\alpha} = A\,(\log \sigma_a - \log \sigma)^{\beta}$$

where T_a, $\log t_a$, A, $\log \sigma_a$, α and β are material constants with alpha ordinarily equal to −1. Sigma is stress.

Attempts to utilize this equation are still awaited; nevertheless, it follows that in any relationship of this type, the more items of test data included and coming from a broad spectrum of testing variables, the greater will be the reliability of the constants and the more accurate will be the extrapolated results. The greatest need is for sufficient application of all such methods of extrapolation so that the conditions under which they will not work are clearly understood. It is doubtful in a phenomenon as complex as creep and rupture that any one correlation will hold for all metals, particularly where rupture lives or limited deformation for time periods of 10,000 to 100,000 hr are desired from short-time tests.

The Larson-Miller relationship, or the methods proposed by Manson are as good as any available for temperature extrapolation of data. Various theoretical and empirical treatments have been proposed which generally relate creep strength to some function of the reciprocal of the absolute temperature. All of these apparently are more limited in range of temperature and applicability to a variety of alloys than the more recent methods described.

There are no foolproof methods for extrapolating values for elongation and reduction of area from short-time rupture tests to prolonged time periods, partly because of lack of understanding of what causes changes in ductility over a range of temperatures and times. Because of intercrystalline cracking, values of reduction of area or elongation at the end of second-stage creep are more reliable for interpretation of metal behavior and short-range extrapolation.

Often there is an intermediate temperature that results in minimum elongation values for a given rupture time. The ductility, especially at the end of second-stage creep (Fig. 9), generally decreases as the rupture time increases with a tendency toward lower values. On the other hand, there are instances when the total elongation and reduction of area increase from a minimum value in more prolonged tests. Again, data for a range of temperatures serve as a guide for probable behavior.

Use of Data on Creep and Rupture

The discussion here will be limited to service conditions that can be approximated with tensile creep-rupture tests at constant temperature and steady load. Information on more complex operating conditions is supplied in subsequent paragraphs.

Metallurgical variables can introduce variations in strength at high temperatures equal to those encountered at room temperature from such factors as heat treatment, cold work, manufacturing methods and fabrication conditions. Consequently, it is essential that data used should be applicable to the final form of the metal. Even where these factors are held constant, some scatter in properties must be expected. Therefore, it is desirable to have as many data as possible from more than one lot of metal in a form as nearly as possible like the one that will be used in service. The ASME-ASTM Joint Committee on the Effect of Temperature on the Properties of Metals has issued several reports of correlated data of this type (ASTM Spec Pub 100, 124, 151 and 160) and is continuing to accumulate such data for future publication. Several firms that manufacture alloys publish statistical test data for their products, showing the normal scatter to be expected in properties.

The procedure used by the Ferrous Section of the ASME Boiler Code Subcommittee on Allowable Stresses as a basis for their allowable stress tables was recently published in Section I of the Code for Power Boilers and Section VIII of the Code for Unfired Pressure Vessels. The subcommittee established design criteria for equipment that operates under the ASME Boiler Code:

1. The allowable stress was restricted to ¼ of the tensile strength, or 62.5% of the yield strength for 0.2% offset up to the temperature where creep and rupture strengths become lower.
2. In the temperature range where creep governs performance, the maximum allowable stress for unfired pressure vessels was restricted to 100% of the creep strength for 0.01% per 1000 hr or 100% of the 100,000-hr rupture strength, whichever is lower. For the Power Boiler Code, the maximum stress was restricted to 100% of the creep strength for 0.01% per 1000 hr, or 60% of the average 100,000-hr rupture strength and should not exceed 80% of the lowest reported 100,000-hr rupture strength.
3. The available data for steels under applicable specifications were reviewed and conservative average values established. Most of these data have since been published in the four ASTM publications mentioned earlier. Curves of the tensile, yield, creep and rupture strengths were plotted to define the governing strength values as functions of temperature. Fig. 11 is an example of this treatment of data for 18-8 stainless steel.
4. Figure 11 illustrates another principle in that there was a wide difference between yield strength and the tensile, creep, and rupture strengths for 18-8 stainless steel up to quite high temperatures because of the low yield strength. For applications where yielding is not serious and where severe stress concentrations are not anticipated, it was considered safe to design up to ¼ of the tensile strength as long as this stress did not exceed 90% of the yield strength or the applicable creep and rupture strength limitations.
5. For nonferrous metals, different criteria are used for unfired vessels.

In many service conditions the amount of deformation is not critical and relatively high fractions of the rupture strength can be used in design. Under such conditions with the combined uncertainties of actual stress, temperature and strength, it may be important that failure should not occur without warning. In such instances, it is necessary that the metal retain high elongation and reduction of area throughout the service life. Many applications of tubing under high pressure in the oil and chemical industries require high, long-time ductility, so that warning of impending rupture will be evident from bulging of the tubes.

Elongation and reduction of area values from rupture tests are used in judging the ability of metal to adjust to stress concentration. The requirements are not well defined and are controversial. Most engineers are reluctant to use alloys when elongations are less than 5%, with the limit sometimes considerably higher. Low ductility in the rupture test almost always indicates high resistance to relaxation of stress by creep, with consequent probable sensitivity to stress concentrations. Large changes in elongation with increasing fracture time are also positive indicators of extensive structural changes in the metal or of surface corrosion.

Relaxation Tests

Relaxation tests measure the rate at which the stress that is present in a part is reduced as elastic strain is replaced with plastic (creep) strain. The decrease in elastic strain is equal to or less than the increase in plastic strain. If the stressed member is not rigidly fixed in length so that the creep strain replaces elastic strain over a longer length than the heated portion in which creep occurs, an "elastic follow-up" will maintain the stress at a higher level than if the stressed member were rigidly fixed. When a flange has considerable elastic deformation and is so cold that relaxation does not occur or when only a part of the length of a bolt is hot enough to creep, the higher level of stress will prevail. Tests are conducted under both conditions so that the data can approximate conditions ranging from ideal relaxation to the infinite elastic follow-up of the constant-load creep test.

Most tests are made without elastic follow-up (fixed total strain). Figure 12 shows a family of relaxation curves for this condition from tests in a unit where the stress was adjusted continuously to maintain fixed total strain. Data have been published for units involving various stepwise adjustments of stress. Sometimes, the steps are made quite large and the residual stress-time relationships are computed from the creep data for the individual steps. The basic data in all tests, with or without elastic follow-up, are the relations between time and residual stress.

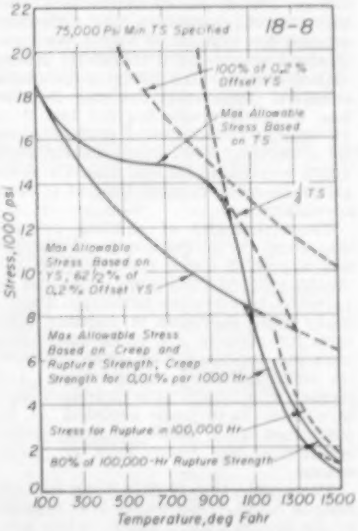

Fig. 11. Relationships Between Strengths at High Temperatures and Temperature as Used by ASME Boiler Code Committee to Establish Maximum Allowable Stresses in Tension for 18-8 Type Stainless Steel

Tests may be quite short in duration for data useful in estimating conditions for thermal stress relief. Longer tests are run to obtain data for bolting, shrink fits, and similar applications, although most testing is limited to 1000 to 2000 hr. Relaxation data are extrapolated mainly by empirical methods involving graphical constructions. Both log-log and semi-log extrapolations are used. For structurally unstable metal, neither may work well.

Relaxation test data are probably most useful for evaluating relative relaxation strengths of metals. Appropriate consideration of elastic follow-up, together with relaxation in threads and gaskets, can be used in the design of bolts and other parts that operate under conditions of relaxation. Although the use is not widespread, relaxation characteristics can be helpful in establishing the most effective thermal stress relieving treatments.

The most difficult problem in the use of creep-rupture data involves knowing the actual service conditions so that the data can be applied efficiently. Seldom are the temperatures and loads accurately known, steady and uniform. Stress gradients are frequently present, as in a vessel under internal pressure with an initial maximum elastic stress at the inner wall surface. If relaxation strengths are low and the wall thickness not too great, the stress gradient is rapidly removed and the average stress can be applied to creep data. This assumption is included in many formulas for obtaining stresses in pressure vessels. However, if creep resistance is high and relaxation of stresses to a uniform distribution is slow or is not attained, the controlling stress is higher than the average, and design should be based on a higher stress than the average.

Combinations of stress and temperature gradients lead to critical sections where creep is at a maximum. In a gas turbine blade, for example, the load from centrifugal force increases from the tip to a maximum at the root in the presence of a temperature gradient along the length. Analysis of the interrelation of the two will establish a point along the length where creep will be concentrated and control the design and choice of metal. In such applications, 1% over-all creep may come from a localized creep of 10% over a relatively short segment of the hot part.

Rupture Testing of Notched Specimens

Notched specimens are being used to an increasing extent in rupture testing as an aid in the selection of alloys and the establishment of proper heat treatments for service where stress concentrations may be present. The most common practice is to use a circumferential 60-deg V-notch in round specimens with a cross-sectional area at the base of the notch one-half that of the straight section. The root radius at the bottom of the notch is carefully machined or ground because it can have a pronounced effect on the results of tests through its influence on stress-concentration factors. Other forms of notch and specimen are sometimes used.

Test results have been reported ranging from increases in life in comparison with unnotched specimens, through no effect, to reduced life (Fig. 13). Certain alloys and test conditions show increased life at high nominal stresses (short rupture times) and reduced life at lower nominal stresses (longer rupture times) resulting in the stress-rupture time curve for the notched specimens crossing the curve for unnotched specimens as the nominal stress is reduced. Still lower stresses may show recovery from notch sensitivity at still longer times for rupture, as occurred in the tests of Fig. 13. These results are found for simple, constant-load tension tests in which the nominal stress is computed by dividing the load by the minimum cross-sectional area at the base of the notch. When increased rupture time is observed in the presence of a notch, the alloy is said to be notch insensitive (notch strengthened), and notch sensitive (notch weakened) when rupture time is reduced.

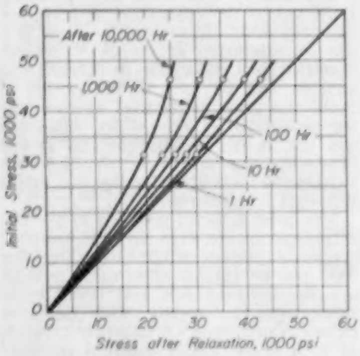

Fig. 12. Relaxation of Cr-Mo-V Bolt Steel at 850 F

A given alloy may show notch weakening at some temperatures and notch strengthening at others. In general, notch weakening appears to increase as the test temperature is reduced. Changes in heat treatment of some alloys may alter the notch sensitivity drastically. The notch configuration itself can have a profound effect on the test results, particularly in notch-weakened alloys.

The influence of the notch configuration appears to be a fairly complex matter. Most studies of this factor present the results in terms of the elastic stress concentration factor. The ratio of rupture strength of notched to unnotched specimens for ductile metals usually increases to some maximum as the stress concentration factor is increased. For very insensitive alloys there may be little further change. Metals that are more notch-sensitive may undergo a reduction in ratio as the notch sharpness (stress-concentration factor) is increased beyond the maximum and may show notch weakening for sharper notches. Very notch-sensitive alloys may undergo little or no notch strengthening, even for very blunt notches (low stress-concentration factor), and undergo progressive weakening as notch sharpness increases.

Stress-concentration conditions depend greatly on the notch configuration and, for the notch conditions ordinarily used, particularly the radius at the root of the notch. The minimum root radius that can be machined accurately is about 0.005 in. The conditions of machining the notch can influence test results to a marked extent, particularly for notch-sensitive materials. Control of machining procedures in addition to dimensional control is therefore necessary to obtain reproducible data and agreement among laboratories. Both residual stresses from machining and structural alteration of the metal directly under the notch could be involved. For specimens of many metals, turning results in longer life than careful grinding. It seems necessary to strive for a clean cutting action with a minimum depth of disturbance of the metal.

Stress analyses show that rather high stress concentrations occur at the base of a notch. If yielding occurs during loading, the stress is redistributed more uniformly across the section and the stress concentration at the base of the notch is reduced. Under creep conditions, reduction of stress concentration can occur after a load has been applied, through redistribution of stress by relaxation from creep. Either or both mechanisms reduce the differences that arise between principal stresses as a result of triaxiality introduced by the circumferential notch.

The effective stress causing creep under complex stresses seems to depend on differences between principal stresses (maximum shear strain energy theory). If the stress redistribution proceeds sufficiently, the effective stress can be less than the nominal stress, and rupture life can be prolonged beyond that of an unnotched specimen under the same stress. If yielding does not occur during loading and the resistance to the stress relaxation by creep is high enough, a high level of stress is maintained at the base of the notch long enough to reduce life in a rupture test.

For notch strengthening to occur, the metal must be ductile enough to permit the plastic deformation necessary to relieve the stress concentration. For this reason, elongation and reduction of area for unnotched specimens have received considerable attention. Alloys of low ductility are likely to be notch sensitive. Apparently the only correlation is notch weakening for less than 2% ductility and notch strengthening for more than 12%. Many metals show notch weakening for less than 5% elongation in creep-rupture tests of smooth specimens.

The complexity of yielding, relaxation from creep, metallurgical change, and degree of stress concentration indicates that ductility alone would not be expected to correlate perfectly. Abnormally rapid decreases in ductility with time for rupture are often associated with the appearance of notch sensitivity with increased rupture time. Increases in ductility with increased rupture time have been reported to be associated with recovery from notch sensitivity, but there may be other causes.

The application of data from rupture tests of notched specimens is at present in the developmental stage. When possible, tests should be conducted with a stress system and concentration approaching those expected in service. For instance, metals for gas-turbine buckets and disks are frequently evaluated with notches approximating those introduced by the blade-fastening serrations. The widest use involves comparison of alloys under certain stress concentrations rather than direct application to service conditions where it is difficult to estimate existing stress conditions. Notched specimens have been used in acceptance testing of individual alloys subject to variation in notch sensitivity with the conditions of manufacturing and heat treatment.

Intermittent (Slow) Load and Temperature Cycling

Some uncertainty arises in the use of conventional constant-temperature, constant-load creep and rupture data in the design of structural parts involving occasional interruption or slow cycling of load and temperature. While the effect of periodic interruption of load and temperature may be investigated experimentally and compared with corresponding static-creep data, it would be impracticable to duplicate all the variations and sequences of load and temperature cycles that might be encountered in actual service. Thus various attempts have been made to establish trends and generalizations that might be used as a guide in applying available static-creep and rupture data to conditions of intermittent load and temperature. A number of experimental methods and test results have been summarized in a recent ASTM symposium (ASTM Spec Pub 165, 1954).

Most structural metals that are ultimately selected for high-temperature applications are chosen because of relative structural stability in the specified

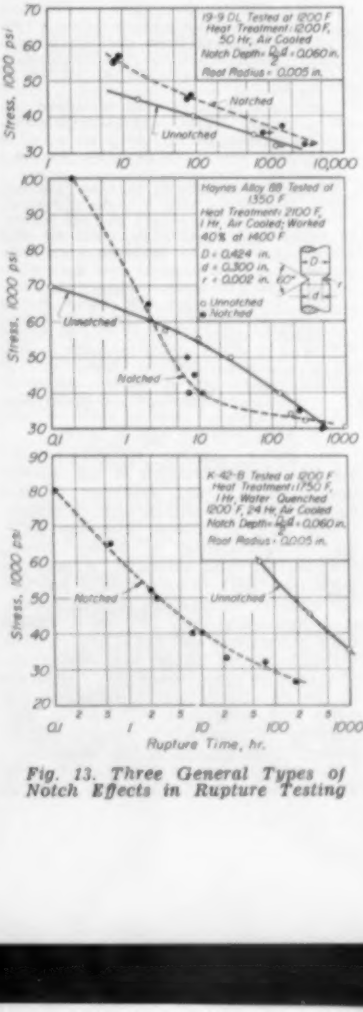

Fig. 13. Three General Types of Notch Effects in Rupture Testing

temperature range. Some alloys, however, are structurally unstable or become so beyond a narrow range of service temperature. The response of these to cyclic effects is important.

Several factors contribute to the creep behavior of an alloy subjected to intermittent load at constant temperature or intermittent temperature at constant load. Even in the "slow" range of temperature and stress cycling, the relative rates of change are still important, and the more rapid changes are more effective in causing deviations in behavior. Stress relief, recovery, or even recrystallization may occur during the load-off heat-on portion of a cycle, thereby contributing to accelerated creep during the subsequent load-on period.

On the other hand, some alloys show actual recovery of creep strain during the load-off part of the cycle, resulting in a net retarding of creep relative to constant-load conditions. In 24S-T3 precipitation-hardened aluminum, overaging occurs more rapidly at 600 F under cyclic load than under static load, leading to the accelerated deterioration of high-temperature strength.

Intermittent changes in temperature may accelerate creep where stress, time and environmental conditions are such as to cause intergranular deterioration. Surface notches, acting in conjunction with cyclic thermal stresses, accelerate creep-rupture with reduced ductility.

While there are very large gaps in the data and knowledge of the effects of cyclic temperature and stress, there is evidence that the effects are more severe when occurring in the first stage of creep and at higher temperatures. Data suggest that for several alloys the effects of temperature and stress cycles are additive. Over-temperature and over-stress cause more damage than cycles involving decreases in temperature and stress.

In view of the various effects that might contribute either to the acceleration or deceleration of creep under intermittent conditions of load and temperature, it would appear preferable to establish typical behaviors for various alloy systems. Table I summarizes the effect of intermittent load and temperature on the creep and rupture properties of several alloys in sheet form.

Dynamic Creep and Fatigue Properties

Just as under static loading both creep and rupture properties must be considered, similarly under cyclic stress loading both dynamic creep and fatigue properties may require attention.

A representative stress range diagram for dynamic creep and rupture is shown in Fig. 14. This diagram shows the combinations of mean stress and alternating stress that lead to rupture, to 0.5% creep, and to 0.2% creep in either 1 or 50 hr. Also shown for later reference are a series of radial lines from the origin to indicate where the alternating stress is 0, 25, 50, 75, 100, and 150% of the mean stress (or static preload). The horizontal abscissa line corresponds to static loading (zero alternating stress), and the curve values along this line give the creep-rupture strength and the stress for the specified creep. The vertical ordinate line corresponds to reversed stress conditions (zero mean stress), and the curve values along this line give the reversed-stress fatigue strength. In between these two limits, both static and fatigue conditions are active and both must be considered as factors in the behavior of metal. This type of diagram is intended to indicate the relative importance of dynamic creep and of rupture at various stress combinations.

Under reversed-stress loading, the tensile creep during the tensile portion of the stress cycle is ordinarily about equal to the compressive creep during the compressive stress portion, with a net effect per cycle of zero. Therefore, very high reversed stress can generally be imposed without excessive dynamic creep; in fact, the creep curves in Fig. 14 lie above the rupture curves and approach the ordinate axis as a vertical asymptote. The portions of the creep curves that lie above the rupture curve are, of course, quite meaningless, since rupture will occur before the specified creep is reached. At low ratios of alternating stress to mean stress (see 0.25 radial line, for example), combinations of stress significantly below those required for rupture may produce significant dynamic creep. Thus, fatigue failure generally determines allowable stress at high stress ratios, whereas dynamic creep becomes a design consideration for low ratios of alternating-to-mean stress. The ratio at which the dynamic creep and rupture lines intersect (below this intersection dynamic creep governs and above it rupture governs) depends on several variables including testing temperature, metal and the magnitude of creep allowed, as shown in Fig. 14.

Another feature of the dynamic creep and rupture curves at low ratios of alternating stress to mean stress is that they are generally close to vertical. This means that the superposition of a relatively small percentage of alternating stress does not greatly affect the allowable mean stress for a given rupture or creep life. Although this generalization appears to hold for smooth specimens of a variety of heat-resistant alloys, as well as the aluminum alloy shown in Fig. 14, different observations have been made of notched specimens. If stress raisers are present, a relatively small percentage of alternating stress may decrease the allowable mean stress.

Although the data shown in Fig. 14 are for relatively short times, the general pattern of behavior shown is also representative of long-time properties. The frequency of cyclic stress may be an important variable in determining the relative importance of dynamic creep and rupture in a given application. Work done on frequency effects has not been sufficient to permit generalizations at this time.

Compression, Shear, Bending, Bearing and Multiaxial Loading

Most of the creep data available have been determined under loading conditions of simple uniaxial tension. However, a number of structural parts, exposed in service to conditions for high-temperature deformation, are subjected to various forms of stress such as bending, shear, bearing, and compression, as well as multiaxial combinations thereof. For lack of actual creep data, engineers have designed such high-temperature members as piping, beams, columns, and riveted joints primarily on the basis of tension-creep properties.

Compression-creep testing of both bar

Table I. Effect of Intermittent Load and Intermittent Temperature Relative to Constant Load and Temperature on the Creep and Rupture Properties of Sheet Alloys(a)

Alloy	Temperature, deg Fahr	Intermittent Load at Constant Temperature (b)		Intermittent Temperature at Constant Load (c)	
		Total Deformation	Rupture	Total Deformation	Rupture
Type 321 stainless steel, annealed	1200	Accelerated	Accelerated	Accelerated	Accelerated
	1350	Accelerated – short time	Accelerated – short time	Accelerated	Accelerated
	1350	No effect – long time	Delayed – long time	....	....
N-155 alloy	1350	Delayed	Accelerated	No effect	Accelerated
	1500	No effect	No effect	....	Accelerated
Inconel X, aged	1350 and 1500	No effect	No effect	Slightly accelerated	Accelerated
24S-T3 aluminum	300	....	Accelerated	No effect	No effect
	450	Accelerated	Accelerated	No effect	No effect
	600	Accelerated	Accelerated	Accelerated	Accelerated
AZ31B-H magnesium	300	No effect	Delayed	Slightly accelerated	Slightly accelerated
	450	Slightly accelerated	Delayed	Slightly accelerated	Slightly accelerated
Titanium, 70,000 psi YS	700	Accelerated	Accelerated	....	....
	800	No effect	No effect	No effect	No effect
Titanium, 110,000 psi YS	700	Delayed	Delayed	No effect	No effect
	800	Delayed	Delayed	No effect	No effect
4130 steel, normalized	800	No effect	No effect	No effect	No effect
	1000	Slightly delayed	Accelerated	Slightly delayed	Slightly delayed

(a) Comparisons of static versus cyclic creep and rupture made after correcting the total elapsed time for the actual time at load or temperature. "Accelerated" or "Delayed" refers to a difference of approximately 50 to 100% in time or a difference of 5 to 15% in stress. "Slightly accelerated" refers to a difference of approximately 0 to 50% in time or 0 to 5% in stress. (b) Load on 1 hr, off 1 hr. (c) At temperature 1 hr, cooled 1 hr and sheet material has been stimulated recently by the buckling problem encountered in heated structural parts of high-speed aircraft. For a variety of sheet alloys including 24S-T3 aluminum, titanium, 4130 steel, and type 321 stainless steel, almost identical creep behavior in tension and compression has been observed in the longitudinal direction of the sheets. In some alloy bars, worked preferentially in the longitudinal direction, creep in compression has been observed to be more rapid than in tension. The metal-ceramic materials have displayed compression-creep strengths three to four times as great as those in tension. Undoubtedly, behavior of such materials in tension is governed by the metal binder, while compressive strength is controlled by the mutual supporting action of the hard intermetallic particles.

Few data on creep in torsion exist, although testing techniques have been investigated (F. L. Everett, Trans ASME, 53, APM 53-10, 1931). From the more practical standpoint of correlating riveted-joint failures under high-temperature shear loading with tensile stress-rupture properties, data of the type in Table II have been obtained. These are results from the same alloy tested both in tension in the conventional manner and as a shear pin in a simple shear blade and clevis holder.

Results from creep-rupture tests of bearing loads in sheet metal also have been obtained at elevated temperatures and correlated with tension for guidance in design. The results presented in Table III represent the ratio of stresses for rupture obtained from the same sheet alloys subjected both to bearing loads and tension.

From the few creep studies made in bending, several procedures have been suggested for calculating the deflections and stress distributions in beams from tension data by assuming that the individual fibers creep in bending as in metal loaded only in tension or compression (E. A. Davis, Trans ASME, 60, A-29, 1938). These calculations are based on experimental demonstration that plane sections remain plane after creep in bending (G. M. McCullough, Trans ASME, 55, APM-55-9, 1933).

The problem of creep in members subjected to conditions of multiaxial loading has been investigated experimentally with the main objective of establishing procedures for relating creep behavior in tension to that associated with the principal stresses of more complex loading. A representative analysis of this type is that of the modified St. Venant theory whereby formulas are derived for creep rates in the directions of principal stresses (J. Marin, "Mechanical Properties of Materials and Design", McGraw-Hill, 1942). Fair confirmation of this analysis has been obtained over limited ranges of temperatures and stresses.

In view of the several idealized conditions, such as isotropy and homogeneity of material, which must be postulated in stress-analysis procedures, considerable caution should be used in correlating tension creep behavior with creep resulting from other forms of loading in metals that have not been investigated experimentally under the stress conditions of interest.

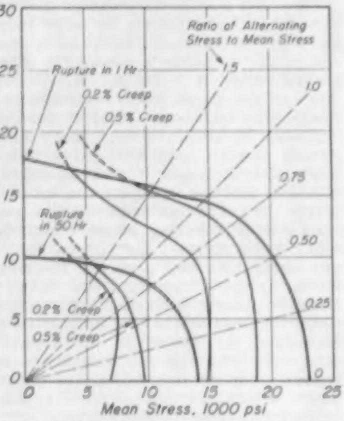

Fig. 14. Stress Combinations for 0.2 and 0.5% Creep and Rupture for 24S-T4 Aluminum at 500 F. Cycle stress applied 3600 times per min

Effect of Test Atmosphere

The role of corrosive and otherwise reactive gases in the atmosphere is an important one in determining the creep behavior of most metals and alloys. Oxidation, which is probably the best understood of this class of effects, has been studied in greatest detail and its large and important effects are well known.

Since one of the purposes of creep testing is to evaluate metals under conditions of atmosphere similar to service conditions, the effects of oxygen, nitrogen, water vapor, carbon dioxide, sulfurous gases, ammonia, carbon monoxide and hydrocarbon reducing gases are all important. The effects of leaded fuels on metals and of attack by molten vanadium oxide and molybdenum oxide "slags" are also of interest.

Table II. Ratios of Stresses for Shear Versus Tensile Creep-Rupture

Alloy	Temperature Range, deg Fahr	Range of Rupture Time, hr	Ratio of Shear Stress to Tensile Stress
24S-T3	300 to 600	10 to 200	0.43 to 0.62
A17S-T4	300 to 600	10 to 200	0.55 to 0.69
Monel	1000 to 1200	10 to 200	0.63 to 0.72
301 stainless	1200 to 1350	10 to 200	0.68 to 0.74

Table III. Ratios of Stresses for Bearing Versus Tensile Creep Rupture(a)

Alloy	Temperature Range, deg Fahr	Range of Rupture Time, hr	Ratio of Bearing Stress to Tensile Stress
24S-T3	300 to 600	10 to 200	1.50 to 1.61
Titanium(b)	700 to 800	10 to 200	1.62 to 1.76
4130 steel(c)	800 to 1100	10 to 200	1.67 to 1.77
321 stainless	1200 to 1350	10 to 200	1.66 to 1.96

(a) Bearing tests conducted with ⅛-in. hole diameter and ratio of edge distance to diameter of 1.5. (b) 110,000 psi min design yield strength. (c) Normalized

Specific metals and alloys are more resistant to certain of the reactive atmospheric phases, but even these are frequently subject to a combination of damaging effects. Thus high-nickel or nickel-base alloys are damaged more severely by sulfur than are iron or iron-chromium alloys. They are, however, more resistant to corrosion by vanadium oil ash and to carburizing atmospheres than are iron and iron-chromium alloys.

The effects of intergranular attack are always more severe than those of general surface reaction. This is especially true since most alloys are subject to intergranular fracture as the normal fracture mechanism in high-temperature creep; the effect is accentuated by any other intergranular process.

The size of the test specimen becomes important when contemplating a corrosive atmosphere, since specimens of smaller diameter are damaged more for a given amount of surface attack or intergranular penetration.

Whereas most atmospheric effects result in poorer creep performance, there are instances where benefits are attained. For example, some of the stainless steels show better properties in oxidizing atmospheres than in inert or reducing atmospheres, and titanium alloys increase in strength and creep resistance above about 1200 F, because of oxygen absorbed from the atmosphere

The obvious answer to the problem of atmospheric effects in creep is to test specimens of cross section as nearly representative as possible in the atmosphere of the application if a considerable effect is anticipated.

Holding Time, Aging, Stabilization

Because of instabilities caused by carbide precipitation, oxidation, aging and other structural changes, it is important in creep testing to consider changes that might occur if specimens are held at temperature for significantly different periods of time before applying the load.

An assessment should be made of available equipment to determine a convenient minimum time necessary to charge a specimen into a creep furnace, adjust temperature and load. A figure somewhat in excess of this minimum value should then be utilized as the standard time for test preparation. Most stable alloys that are pre-aged or heat treated to produce a stable structure are not affected adversely by the atmosphere. However, the influence of the atmosphere would be significant for a program of creep tests from 1350 to 1700 F on an alloy such as one of the nickel-base alloys hardened by titanium plus aluminum, which overages rapidly above about 1500 F; a difference in furnace holding time at 1600 F of 1 hr versus 16 hr makes a great difference in the creep-rupture data.

In general, alloys intended for long-time creep testing will not be seriously affected by the length of the holding time, but for tests lasting less than about 100 to 500 hr, the effect can be significant.

Radiography of Metals

By the ASM Committee on Radiography

RADIOGRAPHY is a method of nondestructive inspection that produces a shadow image of the exterior and interior of an object by means of variations in absorption in the object of penetrating radiation from a radiation source, and the registration of the varying intensities on an image-detecting medium.

Generally, discontinuities which present to the axis of radiation a dimension of from ½ to 2% of the thickness of the object under examination will be detected, provided that acceptable geometry, source size, radiation energy and intensity, image detectors and processing conditions are employed.

The severity or rigor of a radiographic examination is expressed in terms of the visibility of a test object called a penetrameter. Penetrameter visibility, hence radiographic sensitivity, is expressed as the smallest thickness of metal that can be detected, as a percentage of the total thickness being examined. Smaller percentages represent greater sensitivity.

For a discussion of the basis for selecting radiography and other methods of nondestructive inspection, the reader may refer to the article on pages 159 to 163 of the 1954 Supplement of the Metals Handbook.

Radiographic Systems

A radiographic system consists of two components—a source of radiation and a detecting medium or device that can provide a graphic representation of the internal details of a metal part. The source of radiation is either an x-ray machine or a radioactive source, natural or artificial, such as radium, cobalt-60 or iridium-192. X-ray film, which is especially sensitive to x-rays or gamma radiation, is the most common medium for recording images.

Fluoroscopic screens reveal instantaneous images by converting x-radiation into visible light. The screen can be observed by the interpreter or can be photographed for a permanent record that can be examined more leisurely. The latter technique is known as photofluorography.

Application of Systems

Various arrangements of components give rise to the following uses for radiographic systems:

Transmission Radiography. The radiation penetrates the object before reaching the image detection medium (film or screen). The image, a geometrical projection of the object, shows the external and internal details by difference in the amounts of radiation transmitted. The limit of visualization is influenced by the differential change in transmitted radiation, the sensitivity of the detecting medium, its resolving power, the geometry of the system, and the conditions for viewing the image.

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Autoradiography. Here the sample being examined is its own source of radiation; hence it must be radioactive. The recording medium (usually film or plate) is placed against a smooth surface; the autoradiation coming from within the sample produces a transmission radiograph of the metal structure just below the surface of the sample, or of a surface coating.

Reflection Radiography. The object is stimulated to give off radiation so as to make a synthetic autoradiograph. Normally, radiation from an x-ray machine is passed through a relatively insensitive photographic film in contact with a smooth surface of the sample; photoelectrons released from the surface of the part constitute the image-forming radiation. Since the electrons are released in varying intensity according to the atomic numbers of the elements present, the image discloses the nature and distribution of the elements at the surface.

Autoradiography and reflection radiography are not used outside of laboratories, since they are highly specialized and require unusual techniques. The remainder of this article is limited to transmission radiography.

Arrangements of Components of the System

Panoramic. When several objects are arranged in an array around a source of radiation and exposed simultaneously, the setup is called panoramic.

Magnification. Because the radiographic image is formed by projection, it is always magnified at least slightly. Whenever the radiation source is small enough for the image to remain sharp, the object may be placed some distance from the film or screen, near the radiation source, so that it will be magnified further. Magnification up to about 3 diam may be used, enabling easier visualization of small details.

Stereoradiography. Stereoscopic radiographic views can be obtained by making two exposures of the object at slightly different angular projections; the procedure involves shifting the radiation source, with respect to object and film, by an amount roughly equivalent in angle to the eye-spacing at the intended viewing distance. Special viewing equipment is commercially available. Successful stereoradiography depends on previous experience in the reading of film and familiarity with the internal and external configurations of the object. Lack of either often prevents visualization in three dimensions.

A specialized variation uses two radiographs with an angular shift up to 90 deg. Measurements made from reference points on the radiographs can be used to reconstruct geometrically the location of an internal defect.

Selection of X-ray Equipment

The "practical thickness range" of various x-ray units for steel is shown in Fig. 1, where the upper and lower limits represent the practical range for an exposure time of 30 min or less, with good technique. The range of all these units can be extended by special techniques as explained later. The more closely crosshatched bars represent 1% sensitivity; the full range shown represents 2% obtainable sensitivity.

To define the range of applicability of x-ray equipment so that it can be used with various metals, it is first necessary to consider the "radiographic equivalence factors" for these metals with reference to steel. These are listed for eight common metals in Table I. For other metals these factors are about the same as for metals of similar density and atomic number shown in Table I. Determining the practical thickness that may be radiographed for various metals is illustrated as follows: Table I shows the radiographic equivalence factor of aluminum as 0.24 for 250 kv. For an x-ray unit of 250 kilovolts peak (kvp), Fig. 1 shows the upper practical limit for steel to be 2 in. The upper practical limit for aluminum would then be 2/0.24 = 8.5 in. (approx).

When deciding on the purchase of x-ray equipment a unit should be

Supersedes the article on page 141 of the 1948 ASM Metals Handbook

chosen with upper thickness range exceeding that immediately needed, because it is generally easier to extend the range downward than upward. After having narrowed the selection of x-ray equipment to perhaps two units from a practical thickness range, the next item to be considered is cost.

Cost of Equipment, both initially and in maintenance, is shown in Table II. This does not include the cost of film, protection, darkroom, operating personnel or overhead, but establishes only the basic cost per year for 10-yr amortization of the purchase price, plus yearly maintenance.

Maintenance Problems usually vary in accordance with the exciting voltage of the x-ray unit or with its complexity. Maintenance costs are associated with x-ray tube replacement (every 600 to 5000 hr) and repairs to cooling-oil pumps, heating circuits, motor-generator sets and other auxiliary equipment. Approximate costs for various x-ray sources are presented in Table II.

Limitations. Some of the limitations of x-ray sources are apparent from Fig. 1. Other factors that should be considered are portability, flexibility, source size, and radiation output. In general the greatest sensitivities possible with x-ray sources range from 2 to 0.5%. If the desired sensitivity is greater, consideration should be given to other methods of inspection.

Selection of Radioactive Sources

The properties of the radioactive sources commonly used for radiography are listed in Table III. The energy of the gamma-ray sources listed determines the radiographic equivalence factors for different metals by comparison with x-ray equipment of about the same energy as listed in Table I.

If the energy values in the second column of Table III are averaged for a given source, the resulting value may be used to get an approximate equivalence factor for the metals listed in Table I. Comparison should be made with the closest value of kilovoltage given in the column headings of Table I, noting that 1000 kv is equal to 1 mev. Such comparisons will be somewhat in error for some sources of activity because of absorption of radiation within the source itself (self absorption). So far no radioactive source is available that is well suited for examination of the light or thin metals.

The more closely crosshatched bars in Fig. 2 represent thicknesses of steel on which 2% sensitivity or better is obtainable in reasonable time; areas at the ends represent poorer sensitivity.

Table II. Approximate Initial and Maintenance Cost of Basic X-Ray Equipment

Type of Equipment	Typical Initial Cost	Cost per Year for 10-Yr Amortization	Average Maintenance Cost per Year	Total of Average Initial and Maintenance Cost per Year
140 kv	$ 6,500	$ 650	$ 575	$ 1,225
250 kv	12,000	1,200	750	1,950
400 kv	16,500	1,650	1,300	2,950
1 mev	25,000 to 55,000	2,500 to 5,500	6,000	10,000
2 mev	100,000	10,000	7,500	17,500
10 to 31 mev	95,000	9,500	5,000	14,500

Another important factor in determining the practical thickness ranges for the radioactive sources (Fig. 2) is the number of roentgens of radiation emitted per curie of the various radioactive materials. For example, one curie of cobalt-60 emits 1.35 r per hr, whereas one curie of cesium-137 emits only 0.39 r per hr. Even if the radiations had the same energy (and they do not), it would require 3½ times as many curies of cesium as of cobalt to achieve the same radiation output or radiographic exposure time.

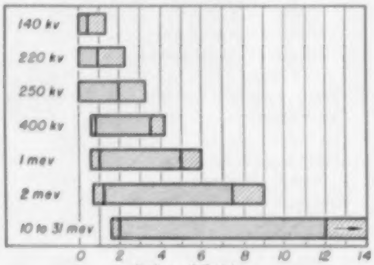

Fig. 1. Approximate Practical Thickness Ranges of Various X-ray Equipment for Steel. The more closely crosshatched bars represent thicknesses where 1% sensitivity is obtainable; the more open crosshatching at ends of bars represents 2% sensitivity.

Another factor is "specific activity" (the number of atomic nuclei disintegrating per second in a given amount of material). Specific activity is usually expressed in curies per gram or curies per cubic centimeter. In Fig. 2, the practical range for steel with cobalt-60 is from ¾ to 8 in., while radium is from ¾ to 5 in., despite the fact that the energy of cobalt-60 is 1.17 and 1.33 mev compared with 0.24 and 2.20 mev for radium. This difference in useful range is a result of the difference in specific activities of the two sources. One gram of radium equals one curie and emits 0.84 rhm (roentgen per hr at 1 meter). One gram of cobalt-60 could equal 20 curies and emit 27 rhm or almost 33 times the amount of radiation emitted by a gram of radium. Although radium has higher energy than cobalt-60, the physical size would have to be much larger to give an equivalent "r" output. This would affect the quality of the radiograph adversely so the upper range of radium has been set at 5 in. compared with 8 in. for cobalt-60 in examination of steel. Enough material should be purchased to allow a reasonable exposure time.

Radioactive sources are either unshielded "free sources" or beamed or positioned by remote control from a shielded position. Only the free sources, handled by cords or "magnetic handling tools", are considered here.

The average activity of sources commonly used, their emission, and a recommended maximum source activity for normal industrial applications are shown in Table IV. The maximum source activity that might be safely employed under special conditions is, of course, determined by the length of time during which personnel are exposed during the radiographic operation, the distance of personnel from the source, and the frequency with which the operation is repeated. All such operations should be subject to monitoring by personnel qualified in radiation safety. Cost of sources is evaluated in Table V.

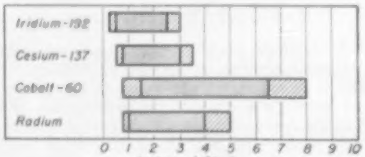

Fig. 2. Approximate Practical Thickness Ranges of Radioactive Sources for Steel. The central, closely crosshatched areas represent 2% sensitivity or better; the areas at the ends represent poorer sensitivity in the practical range.

Limitations of radioactive sources are somewhat different from those of their x-ray counterparts. While exposure times are generally longer for radioactive sources, panoramic setups can be arranged for overnight exposures to counteract this deficiency partially. Usually radioactive sources supplement x-ray equipment; each will have applications for which it is suited better than the other. The radiation quality (energy) of radioactive sources is fixed and cannot be controlled as with x-ray equipment. Radioactive sources are not recommended for the inspection of thin sections or light alloys.

Table I. Approximate Radiographic Equivalence Factors for Several Metals in Relation to Steel

Metal	Density	Radiographic Equivalence Factor 140 kv	220 kv	250 kv	400 kv	1 mev	2 mev
Aluminum	2.7	0.083	0.24	0.24	...	...	...
Magnesium	1.7	0.05	0.08	0.08	...	...	...
Steel	7.8	1.0	1.0	1.0	1.0	1.0	1.0
Stainless (18.8)	7.9	1.0	1.0	1.0	1.0	1.0	1.0
Copper	8.9	1.8	1.4	1.4	1.4	...	...
Zinc	7.1	...	1.3	1.3	1.3	...	...
Brass	8.4	...	1.3	1.3	1.3	1.2	...
Lead	11.3	...	11.0	...	...	5.0	2.5

Adapted from ASTM E94-52T

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An important factor in deciding between x-ray equipment and radioactive sources is whether the metal piece will lend itself to positioning in relation to x-ray equipment or whether a small radioactive source could be positioned more readily. The production load, or number of exposures per day, is also an important factor.

Selection of X-ray Films

Various types of x-ray films are commercially available, differing in speed, contrast and graininess. The success of a radiographic examination depends in large part on the type of film used. In general, the higher-contrast, lower-graininess films are slower but produce images of better quality.

The characteristic curves of two typical films are shown in Fig. 3, in which photographic density is plotted against logarithm of relative exposure to x-rays or gamma rays. Photographic density is defined as log I_o/I, where I_o is the intensity of the light incident on a film, and I is the intensity of the light transmitted. For a particular film, the shape of the characteristic curve is essentially independent of the x-ray or gamma-ray source used, but does depend on processing variables.

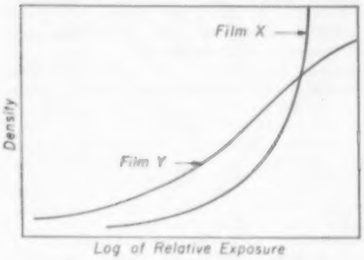

Fig. 3. Characteristic Curves of Two Typical Industrial X-ray Films. Photographic density versus logarithm of relative exposure to x-rays or gamma rays

The slope of the curves of Fig. 3 changes continuously along the whole length of the curve, which in turn affects visibility of detail in the radiograph. For example, two slightly different thicknesses in the object radiographed will transmit slightly different exposures to the film. The ratio of these two exposures will be constant as long as the quality of radiation remains the same, and will be independent of the absolute values of exposure time and intensity of radiation. Therefore, the exposures will have a certain small and constant interval between them, equal to log E (logarithm of relative exposure).

The difference in density of the two exposures will depend on just where they fall on the characteristic curve; the steeper the slope of the curve, the greater this difference in density will be. Thus, with film X the greatest visibility of detail will be obtained by exposing to as high a density as can be allowed by conditions under which the radiographs are to be viewed. Other requirements, such as radiographic speed, might dictate the use of film Y, having maximum radiographic contrast at an intermediate density.

The selection of a film for the radiography of any particular part depends on the thickness and material of the specimen, and the radiation available. Also, the choice is influenced by the relative importance of high radiographic sensitivity or short exposure time.

The diagram in Fig. 4 shows the films that usually prove satisfactory for certain classes of work. (The shaded areas, rather than the lines dividing them, should be considered.) An attempt has been made to balance the two opposing factors of high quality and short exposure time. It is impossible, however, to present definite rules on the selection of a film. If high quality is the deciding factor, a slower, and hence finer-grain film should be substituted for the one recommended. If short exposure times are essential, a faster film should be used rather than the one indicated in Fig. 4.

A process that produces a dry radiograph on paper rapidly is an adaptation from the photographic field. Packets of this paper are exposed and self-developed in a special cassette and developing unit. The image is viewed by reflection, has a narrow range of density, and is therefore considerably restricted in application. The practical advantages and disadvantages are obvious. The cost per sheet of paper is about four times the cost of a sheet of x-ray film at present (July 1955).

Screens

When an x-ray beam strikes a film, usually less than 1% of the x-ray energy is absorbed, and only energy *absorbed* in the film will produce a photographic effect. Obviously, any means of utilizing the unabsorbed part of the energy more fully, without complicating the technical procedure, is highly desirable. Two types of radiographic screens are used to do this.

Lead Foil Screens. Lead foil in intimate contact with both sides of the film during exposure improves the quality of the radiograph by reducing the effect of scattered radiation.

Lead foil screens permit a reduction in exposure time for steel thicker than about 0.25 in. and kilovoltages higher than about 130. In all such exposures the use of lead foil screens is recommended. Because they can improve the quality of the radiograph, lead foil screens may be used sometimes where they increase exposure time.

With gamma rays and with x-rays below 2 mev, lead screen thicknesses are commonly 0.005 in. in front of the film and 0.010 in. behind. The choice of screen thickness for use with betatron radiation is much more complicated; manufacturers or users of the equipment should be consulted for recommendations.

Lead foil for screens must be selected carefully, and the use of commercially

Table III. Radioactive Sources Commonly Used for Radiography

Radioactive Element	Half Life, yr	Energy of Gamma Rays, mev(a)	Gamma Ray Dosage Rate per Curie, rhm(b)	Max Available Specific Activity, curies per cu cm
Radium	1620	0.24 to 2.20(c)	0.84	Variable
Cesium-137	37	0.66	0.39	40
Cobalt-60	5.3	1.17 and 1.33	1.35	180
Iridium-192	70 days	0.137 to 0.651(d)	0.55	1100

(a) Million electron volts. (b) Roentgens per hour at 1 meter, neglecting self-absorption. (c) Eleven principal gammas. (d) Twelve gammas

Table IV. Average Source Activity and Maximum Activity for Free Sources

Source	Average Source Activity, curies	Emission, rhm(a)	Maximum Source Activity, curies	Emission, rhm(a)
Radium	0.2	0.168	2	1.68
Cesium-137	2	0.78	5	1.95
Cobalt-60	0.5	0.625	1.5	2.03
Iridium-192	2	1.1	4	2.2

(a) Roentgens per hour at 1 meter, neglecting self-absorption

Table V. Approximate Cost of Radioactive Sources

Source	Activity, curies	Approximate Initial Cost	Usable Life, yr	Cost per Year
Radium	0.2	...	..	\$600[(a)]
Cesium-137	5	\$750	40	75[(b)]
Cobalt-60	0.5	200	5	40
Iridium-192	2	...	..	900[(a)]

(a) Based on rental. (b) Using 10-yr amortization

available screens is recommended. If screens are to be made by the user, lead coated with tin or with any other material should be avoided, since irregularities in the coating will result in mottled radiographs. Wrinkles and dents in lead screening should also be avoided, since they too will lead to blemishes in the radiographs. An alloy of 6% Sb and 94% Pb has physical qualities superior to, and radiographic properties equal to, those of pure lead.

Fluorescent Screens. Fluorescent screens consist of a powdered fluorescent material in a suitable binder coated on a cardboard or plastic support. For exposure, the film is clamped firmly between a pair of these screens, and the photographic effect on the film is mostly that of the light emitted by the screens. At energies below 400 kv, fluorescent screens permit great reduction in the exposure time, compared with that necessary with lead foil screens. The advantage decreases with increasing energy. However, at all energies, lead screens give better definition compared with that of a radiograph made with fluorescent screens. The poorer definition is caused by the spreading of the visible light emitted from the screens. The light from any individual crystal spreads out beyond the confines of the original x-ray beam that excited the crystal to fluorescence. The overlapping of many such minute areas blurs outlines in the radiograph. Fluorescent intensifying screens are used in the radiography of relatively thick specimens—for example, steel thicker than 1.5 in. at 200 kv, 3 in. at 400 kv, or 6 to 8 in. at 1000 kv.

Fluorescent screens should be used only when the exposure necessary without them would be prohibitive, and the sensitivity that can be achieved is acceptable for the application.

General. Radiographic screens, both lead and fluorescent, should be kept free from dirt, moisture, grease and lint. Such surface contamination will introduce blemishes on the radiograph. Grease and dirt may be removed from lead foil screens by a suitable solvent, or, if more thorough cleaning is necessary, by gentle rubbing with the finest grade of steel wool. Fluorescent screens should be cleaned according to the manufacturer's recommendations.

When intensifying or lead foil screens are used, good contact between screens and film is of prime importance. A vacuum cassette or a rigid spring-back cassette will provide this intimate contact. Rigid cassettes should be tested occasionally for screen contact.

Cardboard or thin plastic exposure holders are cheaper, easier to handle in large numbers, and more flexible than rigid cassettes. However, if screens are to be used in them, special precautions must be taken to insure good contact. The exact means used will depend on the object to be radiographed. Exposure holders may be pressed or clamped against the specimen; or the weight of the specimen or the flexing of the holder, bent to fit inside some structure, may be used to insure good contact.

Photographic Processing

Since the usefulness of a radiograph depends on the processing technique, care and cleanliness in all processing procedures are essential.

Developing solutions should be maintained as close to 68 F as possible. Successful processing cannot be carried out below 60 F or, without special techniques, above 75 F.

X-ray films are usually processed in vertical tanks deep enough for the largest film to be hung vertically. The volumes of the tanks for developer, stop bath or rinse, fixer (hypo), wash, and wetting agent (to hasten drying) should be in the ratio of about 1:1:3:4:1, respectively, to allow a steady flow of films through the processing system and a sufficient time in each bath. The volume of the fixer tank will depend on the types of film processed and the method used to maintain fixer activity.

Assuming a 5-gal developer tank of standard ASA dimensions, and tank volumes for the other solutions in the ratio shown above, 30 to 60 films can be processed and made ready for drying per hour, and the first film will be ready for drying in 30 to 45 min. The processing equipment, exclusive of drying facilities, will occupy 55 to 70 in. of wall space in the darkroom. Larger tanks will permit a correspondingly greater production rate and will occupy proportionately greater space.

Where large volumes of films are to be processed, machines may be used. A typical processing machine commercially available will handle 120 films per hr and will have the first film dried and ready for viewing in about 90 min. Such a unit will occupy about 17 linear ft of space, 8 ft of which are in the darkroom, and is about 3 by 8 ft in maximum cross section.

Costs of processing facilities are difficult to specify, since they depend on the volume of film to be handled, the amount of construction, electrical and plumbing work necessary, and whether manual or machine processing is to be used. The minimum cost of processing equipment that will permit the handling of a few 8 by 10-in. films per day will be about \$150, exclusive of processing room space, plumbing and wiring. An average processing room for manual processing of 175 to 200 14 by 17-in. films per 8-hr day will cost about \$1000. Substituting stainless steel tanks for the cheaper hard rubber type included in the \$1000 figure will increase the total expenditure to \$1500, which will also cover the cost of constructing a suitable darkroom with the necessary electrical fixtures and plumbing.

Viewing of Radiographs

The finished radiograph should be examined under conditions designed for best visualization of detail combined with maximum comfort and minimum fatigue for the observer.

The sensitivity of the human eye to contrast (the ability to distinguish small differences in brightness) is greatest when the surroundings are of about the same brightness as the area of interest. Thus, to see the finest detail in a radiograph, the illuminator must be masked to avoid glare from bright light coming around the edges of the radiograph, or through areas of low density. Subdued lighting, rather than total darkness, is preferable in the viewing room. The illumination of the room must be arranged so that there are no reflections from the surface of the film that is being examined.

Industrial radiographs are often exposed to densities as high as 4.0, to allow the coverage of as wide a range of thickness as possible on a single radiograph or to take advantage of the high contrast of some films at elevated densities. A high-intensity illuminator with adjustable intensity is almost a necessity for radiographic observation and interpretation.

References

American Standard Z38.8.7-1946, "Internal Dimensions for Radiographic Film Processing Tanks", ASA, New York

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Fluoroscopic Screens

The use of fluoroscopic screens in industrial inspection is feasible wherever high sensitivity is not required and speed is important. These screens are especially suited to continuous inspection on a moving belt.

Fluoroscopy is about one quarter as sensitive as a film technique. If measured in terms of visibility of penetrameter images, sensitivity is usually about 10%. It can be extended by careful technique to perhaps 2% in some applications. An equally careful film technique might give ½% sensitivity.

Parts can be inspected as they move through the fluoroscope not in just one projection, but in a continuously changing projection if they are carried through mechanically, or at any chosen angle if they are moved manually. This gives the effect of perspective, so that the depth of discontinuities may be estimated. Fluoroscopy makes it easier to examine otherwise difficult sections, such as a web adjacent to a rib. The changing angle of view increases the probability of aligning crack planes with the radiation beam so that they will be detected.

A common important application of fluoroscopy is in surveying metal parts in production lots to screen out those containing the more obvious defects, before radiographic inspection with film. Besides the economic saving, such a procedure provides a quick indication as to the general quality of the lot.

Practical Limitations. The proper light level for best viewing of the screen is about 1 milli-lambert, which is a value much higher than normally obtained; below this level, the efficiency of the human eye is gradually reduced. The distance between target and screen should be short to provide relatively intense radiation at the screen position. However, too short a distance may not permit a large enough field to cover the parts being examined, or may produce intolerable unsharpness of image because of penumbra.

Adaptation of the eye to low brightness levels must be considered. The inspector may require as long as 20 min for eye accommodation before beginning inspection.

Fatigue is related to several factors, such as the brightness available, the type and rate of objects inspected, the nature of discontinuities, the age, sex, condition of eyes, and practice of the inspector. An average schedule for an inspector might be 2 hr on, then 2 hr off. When fatigue sets in, the operator gradually loses ability to give attention, and inspection becomes not only less sensitive, but also more erratic.

The operator is protected from radiation by a barrier between screen and operator which is reasonably transparent to visible light, but opaque to x-radiation. Glass containing lead oxide or lead silicate is commonly used, or transparent cells containing water solutions or heavy compounds such as lead perchlorate. Tungsten and lead phosphate glasses are not yet in common use but show promise. All these materials absorb a considerable amount of light (up to 30%) even when new. They discolor to varying degrees as a result of exposure to radiation, and absorb even more of the incident light as they age.

Image Quality Limitations. The fluoroscopic screen is made up of a thin layer of crystals mounted on a paper base. Since the amount of x-ray energy that is converted to visible light will depend on the effectiveness of the crystalline layer in absorbing it, a thicker layer will be more efficient than a thinner layer. The screens manufactured for industrial use are a compromise between high brightness (a thick crystalline layer) and high resolving power (thin layer and smaller crystals). Unsharpness in the screen is determined by the minimum size of defect that can be observed and the projection magnification. A considerable selection of screens is available, with unsharpness values ranging from approximately 0.020 to 0.065 in. The screen of finest grain gives approximately half the brightness of the brightest screen.

The contrast sensitivity—that is, sensitivity to small changes in object thickness—depends on the type of radiation, the screen characteristics, and visual response to the level of brightness. The contrast sensitivity is usually much lower than in film radiography; under the best conditions, it may approach that of the low-contrast radiograph.

Another limiting factor in image sharpness is penumbra resulting from the size of the radiation source (focal spot) and the distance by which the discontinuity is separated from the screen. It is likely to be more bothersome in fluoroscopy than in film radiography because of the short target-to-screen distance normally used in an attempt to gain brightness.

Techniques for Best Sensitivity include the following:

1. The brightness level should be no less than 0.01 milli-lambert and preferably closer to 1 milli-lambert.
2. The screen should be as fine-grained and thin as feasible; usually some brightness can be sacrificed in favor of improved sharpness, for an over-all gain in resolution.
3. Target-to-screen distance should be as short as possible, to gain brightness, but the penumbra must not exceed the desired resolution; preferably, the penumbra should not exceed the screen unsharpness.
4. The focal spot employed should be the smallest that will give the x-ray intensity necessary for the desired brightness level; new x-ray tubes appearing on the market can provide a focal spot less than 1 mm.

Photofluorography is the technique of photographing the image on a fluoroscopic screen. It uses radiographic units, films and viewing equipment all specially designed for convenient and rapid use.

Two common systems exist—one using a high-aperture photographic lens and the other, a parabolic mirror—to reduce the fluorescent screen image to the size of photographic film

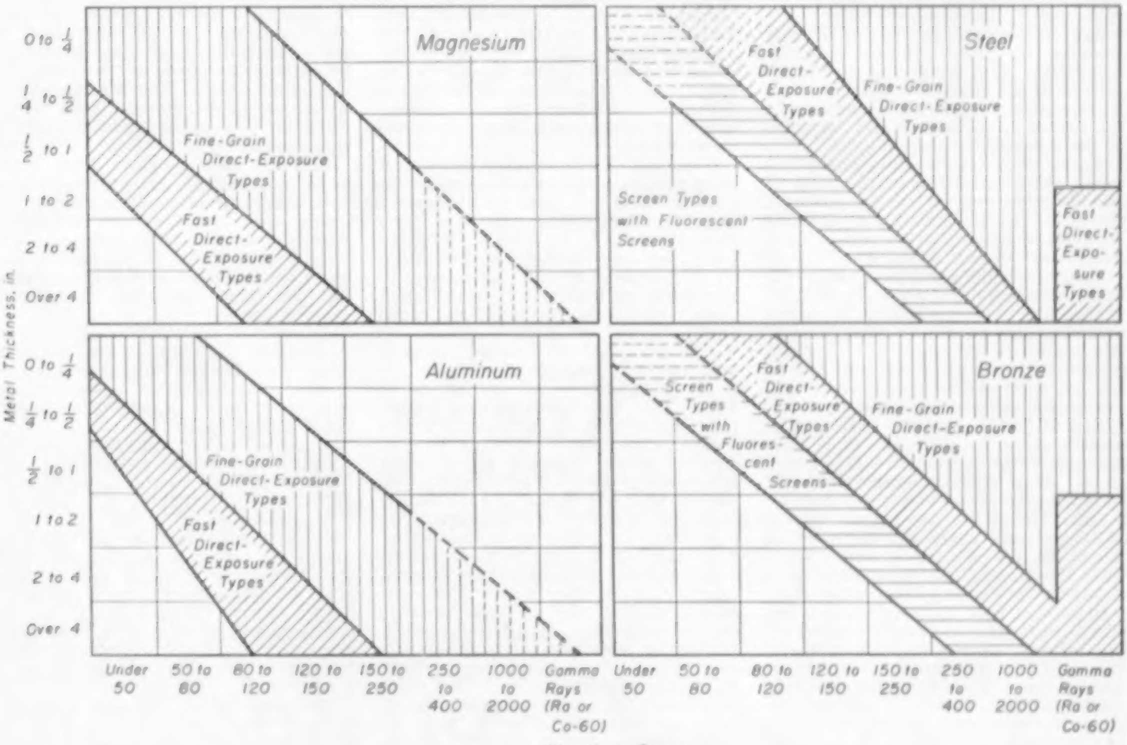

Fig. 4. X-ray Films to Be Used for Different Classes of Work with Magnesium, Steel, Aluminum and Bronze. Shaded areas, rather than lines dividing them, should be considered. Since the chart is based on practical exposure conditions, wherever longer exposures can be tolerated a finer-grain film should be used. "Different classes of work" refers to the thickness of metal or the energy of the radiation source. (ASTM)

desired (ranging from 35-mm roll to 4 by 5-in. sheet film). The film is protected from x-radiation by a barrier or is placed outside the radiation field and "sees" the image through a mirror system.

Obvious advantages are permanency of record and small film size. In addition, the image contrast is enhanced in the photographic process so that the sensitivity is considerably greater than in fluoroscopy.

High-Brightness Fluoroscopy. A new aspect employs electronic apparatus for increasing the brightness of image.

References

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Summary of Limitations of Radiographic Systems

Since a radiographic system depends on the differential absorption of electromagnetic radiation to produce a shadowgraph of an object, the sensitivity limitations of the system are related to the three factors: (1) subject contrast of the object being examined; (2) geometric relationship of the source, object and detecting device; and (3) response of the detecting device.

Subject contrast depends on the differential absorption of the radiation penetrating the object and is directly related to the effective voltage or wave length of the radiation, as well as to the nature of the metals and thickness of the object to be inspected.

There is an inverse relationship between the penetrating effectiveness of the radiation and the subject contrast. Therefore, in general, lower effective voltage should be used for thinner sections and lighter alloys and higher effective voltage should be used for thicker sections and heavier alloys.

The sensitivity of the radiographic system is also limited by sharpness of the shadowgraph resulting from the geometric relationship of the size of the source, thickness of the object, and distance from the film, as well as the source-to-film distance. Radiation sources currently available vary from approximately a fraction of a millimeter to 10 mm in source size, and the thickness of the object can vary by a large factor. For the highest degree of radiographic sharpness, the smallest source should be used in conjunction with the finest-grain x-ray film and the most favorable geometric relation.

In general, both the quality and speed of the radiographic system depend on the response of the film and screens. The use of fluorescent intensifying screens in conjunction with radiographic films will increase radiographic speed. However, the visible detail possible with this system is also reduced. Two per cent sensitivity is common; under closely controlled conditions, with lead screens, sensitivity of ½% is possible.

For fluoroscopic inspection, the limitations are related to the detail available from a fluoroscopic screen, and the response of the screen to effective voltage or energy from the source. Since commercial screens now available are most sensitive at approximately 100 kv, the utilization of this system is limited to approximately 2 in. of aluminum, and routine sensitivity of about 10% can be obtained. With the most careful technique and for the most favorable applications, this may be extended to 2% sensitivity at best.

Safety Requirements

Because x-rays and gamma rays from radioactive materials have a destructive effect on living tissue, adequate protection is necessary. Some of the recommended safety precautions are indicated in the following paragraphs. In addition, the reader may consult the ASA Safety Code for the Industrial Use of X-Rays, and various handbooks of the National Bureau of Standards which are listed on page 191.

Any recommendations or regulations issued by State and Municipal Boards of Health and Labor pertaining to the installation and operation of industrial laboratories that employ x-rays or radioactive materials should also be studied. The specific design recommendations cited in the various references in the field of radiation protection cannot be considered final, since they are based on assumptions that may require revision as additional information is acquired.

Personnel should not be exposed to direct rays from the generating source or to scattered radiation from different objects in the path of the direct beam. While the exposure is being made, the operator and other members of the x-ray laboratory, and persons in adjacent departments, must be protected. Wherever possible the protective measures should be a permanent part of the construction.

Providing the necessary protection from radiation in any new installation may increase the total cost considerably. The added cost can vary from zero, for units in which the manufacturer has incorporated the protection in the design of the apparatus, to thousands of dollars for thick-walled special rooms for the x-ray machines and betatrons of highest energy.

The preferred and most common method of providing protection for units of relatively low voltage is to install the radiation-producing equipment or material in a lead-lined enclosure. Considerable economy may be effected if the quantity of radiation that must be absorbed in the protective walls is kept to a minimum. Lead-lined hoods or cabinets are available, designed for use where large numbers of small castings or parts are inspected on a routine basis. The parts to be exposed, together with the x-ray film, are placed in the lead cabinets through mechanically operated lead-lined doors, electrically interlocked with the x-ray controls to prevent the x-ray tube from being energized before the doors are closed. Small lead-lined cabinets for x-ray units up to 100 kv may be purchased for a few hundred dollars each. Larger cabinets for units of 150-kv capacity vary in price from $2000 to $4500, depending on the number of optional high-production features. Even larger cabinets or hoods for $3000 to $5000 are available for 250-kv units.

For some installations distance alone must be relied upon to provide the proper protection. For example, when the object to be inspected is too large to be transported to the x-ray laboratory, the radiographic testing must be performed on the shop floor. Usually portable lead shields are provided to protect workers in the same area. It may be desirable to enclose a section with ropes and signs, warning the plant personnel to remain at a specified safe distance.

After a new installation is completed, a radiation survey should be made to determine whether the construction and operating conditions are safe.

Protection Against Gamma Rays and High-Voltage X-rays. Radiation from radium or cobalt-60 or from high energy x-ray machines has biological reactions similar to the x-rays from low-voltage units. Knowledge of the proper methods of use and of the necessary protective measures must be demonstrated to the U. S. Atomic Energy Commission before artificial radioactive material may be purchased.

Lead is the major protective material in the low-voltage range but it is used for high voltages and gamma rays only when space is limited. Because of its structural strength, concrete has been favored in the high-energy region, where the absorption is principally a mass effect. Since the thicknesses necessary to attenuate gamma rays are great, the only economical means of protection is a combination of distance and protective material.

The dangerous area around the radioactive material should be indicated and all personnel forbidden to enter this zone except those authorized to position the capsule. Walls, benches and other objects have a serious scattering effect on gamma rays, which must be considered when estimating the possible dosage.

Although the radiation from x-ray units is usually from a fixed position and hazardous only when the unit is in operation, radiation from radioactive sources may arise from different locations in the plant. If radioactive isotopes are scattered, spilled or lost during use, they must be found and cleaned up.

Because of the variable strength of radioactive isotopes, their transfer from the container to one position or another requires strict adherence to code requirements regarding maximum daily dosage rates.

A greater danger than bodily contact with isotopes is the possibility of inhalation of some of the material such as radon from radium or dust particles from cobalt-60 or other radioactive isotopes. Such hazards are unlikely unless the sealed containers in which the radioactive material is encapsulated are damaged by careless handling. When radium or cobalt-60 is not in use it should be kept in a thick lead container or in a hole in the earth deep enough to reduce the radiation to a safe level.

Measurement of Radiation Received by Personnel. A radiation physicist should be consulted in regard to proper techniques for monitoring of personnel and periodic radiation surveys. It may become necessary to measure quantitatively by suitable instruments the extent of the stray radiation in and around a radiographic installation or the amount received by the various employees of the laboratory. Trained personnel should be available to insure the proper use of the various instruments, to interpret the readings obtained, and to make the necessary recommendations for safe practices.

The measurements are usually recorded by either small ionization chambers or photographic film.

The ionization chambers are first charged electrically by a special instrument, carried in a pocket for one or more days, and then examined to determine the extent of exposure. The amount of discharge is usually expressed in roentgen units. A charging instrument and five pocket chambers cost from $150 to $200.

The photographic method of monitoring is inexpensive, convenient and provides a permanent record. Frequently films are used together with ionization chambers as a check. When photographic film is used for monitoring, an estimate of the dosage depends on measurement of the density of the film evaluated in terms of roentgens. A suitable instrument for measuring film densities, such as a densitometer (minimum price, $60), should be available. Special packets of x-ray film for monitoring are sold by the film manufacturers. A complete photographic monitoring service is provided by several commercial laboratories. The cost of such a service varies with the number of film badges used.

All personnel in the department should receive instructions in safe working practices when using x-rays or gamma rays. The nature of the injuries that may result from neglecting to observe the safety rules should be clearly understood. Failure to conform to the established rules should be cause for transfer or dismissal.

Protection of X-Ray Film in Storage. X-ray film in storage must be properly protected against exposure to stray radiation. It is customary to protect film in lead-lined cabinets for kilovoltages up to 200. At higher voltages, protection becomes increasingly difficult because, in addition to lead protection, adequate distance must be provided between the source of radiation and the film.

Table VI. Thickness of Lead Shielding Needed for Surrounding Cobalt-60 to Limit Film Fogging

Distance, ft	Thickness of Lead, In. for Source Strength, millicuries					
	50	100	200	500	1,000	2,000
25	3.0	3.5	4.5	5.0	5.5	6.0
50	2.0	2.5	3.5	4.0	4.5	5.0
100	1.0	1.5	2.5	3.0	3.5	4.0
200	0	0.5	1.5	2.0	2.5	3.0
400	0	0	0.5	1.0	1.5	2.0

During the period when radium and cobalt-60 are being used for radiography, the only practical protection for stored film is to keep it at a distance from the radioactive materials. Table VI shows distances, varying amounts of cobalt-60, and thickness of protective lead that will produce a slight but acceptable degree of fog on a fast, coarse-grain, no-screen type of industrial film when stored for a period of two weeks near the radioactive material.

Table VI is based on cobalt-60, since this material is becoming more common than radium. To apply the table to radium, the source strength should be multiplied by 1.6. Other films may be stored under these same conditions for the following periods:

1 Extremely fine-grain, no-screen type of industrial film—30 weeks
2 Fine-grain, no-screen type of industrial film—12 weeks
3 Screen type of industrial film—4 weeks

Regardless of relative amounts of distance and protective materials employed, or the type of radiation involved, slow films should not receive more than 4 milliroentgens total dose during their period of storage. Faster films should not receive more than 1 milliroentgen exposure.

Because of the deleterious effect of heat and moisture, all film should be stored in a cool, dry place and ordered in such quantities that the supply on hand is renewed frequently. Under no circumstances should film be left in a chemical storage room or in any location where there is leakage of illuminating gas or any other type of combustible gas, or where there is a possibility of contact with formalin vapors, hydrogen sulfide, ammonia, or hydrogen peroxide.

The industrial-safety-base x-ray film presents no greater fire hazard in storage in the x-ray laboratory and filing room than an equal quantity of paper records.

Electrical Safety. The voltages employed to energize radiographic tubes are extremely dangerous. The body must never be permitted to form a part of the high-voltage circuit either across the tube leads or between a high-potential lead and a grounded conductor. Most x-ray generators for industrial radiography are of shockproof construction. Where the design is such that high-voltage conductors are exposed, the high-voltage generators, capacitors, x-ray tubes and conductors should be made inaccessible by means of insulated or grounded enclosures. Any door, gate, port or panel permitting ready access to the interior of a high-voltage area should be provided with reliable interlocks, to de-energize the primary circuit of the high-voltage transformer when they are opened. A switch should be provided within the enclosure, so that anyone within the area can prevent the energizing of the high-tension transformer.

All exposed non-current-carrying metal parts of x-ray apparatus, including protective guards, barriers, enclosures, and shields, should be permanently grounded in accordance with the provisions of the latest edition of the National Electrical Code.

Low-potential electric outlets and fixtures may present a hazard in the processing room. Special care should be taken to prevent the body from becoming part of an electric circuit, since a voltage of 110 or less may prove fatal. No electrical appliance (including electric timers and mixers) should ever be touched with wet hands or while any part of the body is in contact with a grounded conductor, such as water connections, processing tanks, or a wet concrete floor.

High-voltage systems should be inspected at least bimonthly for possible loose parts or faulty insulators. High-voltage barriers and interlocks, and grounded connections should be checked at the same intervals. A general inspection of electrical components should be made at least once a year.

References

"Safety Code for the Industrial Use of X-Rays" Z54.1 (or latest revision thereof), ASA, New York

National Bureau of Standards Handbook 41, "Medical X-Ray Protection Up to Two Million Volts"

National Bureau of Standards Handbook 42, "Safe Handling of Radioactive Isotopes"

National Bureau of Standards Handbook 50, "X-Ray Protection Design"

National Bureau of Standards Handbook 51, "Radiological Monitoring Methods and Instruments"

National Bureau of Standards Handbook 54, "Protection Against Radiation from Radium, Cobalt-60 and Cesium-137".

National Bureau of Standards Handbook 55, "Protection Against Betatron—Synchrotron Radiations Up to 100 Million Electron Volts"

National Bureau of Standards Handbook 59, "Permissible Dose from External Source of Ionizing Radiations"

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Application to Control of Manufacturing Processes

Radiography is most economical in developing methods of production and in maintaining quality control. These purposes are well illustrated by the application to production of steel castings.

The first casting produced is carefully radiographed to determine the effectiveness of the foundry technique. Special attention is given to areas known to be highly stressed in service and areas to be machined. Shrinkage areas may vary widely in degree and only a knowledge of the actual service conditions of the casting will enable an intelligent evaluation to be made of the radiographs obtained when the pilot casting is examined. As changes are made on subsequent castings the results can be evaluated quickly.

Once a satisfactory foundry practice has been established, radiography is then used to control quality. If a large number of castings are to be made, the amount of radiography can be reduced by a sound plan of statistical quality control.

Another example of the application of radiography to manufacturing process control is in welding. Radiography is commonly used in the qualification of welding operators. The operator's ability to produce satisfactory weld deposits in the various welding positions can be determined quickly by an examination of the radiographs of the welds produced on test plates.

Welding deficiencies and incorrect

welding practices are readily detectable in the radiographs. This demonstrable evidence of welding errors is also a valuable aid in the instruction of welding operators.

Radiography is often used to check a series of joints produced with systematic changes in one or more variables and to serve as a qualification of the welding practice.

After both the practice and operators have been qualified, radiography is then employed to insure adherence to the proved method and as a check on quality. As with castings, repetitive work enables the amount of radiography to be regulated by methods of statistical quality control.

Application to 100% Product Inspection

The mechanization of radiographic inspection for large and complex castings and welded structures has not advanced so rapidly as the mechanization of foundry and welding processes. Consequently, 100% inspection of such products by radiography can represent a serious production bottleneck. In general, the slowness and high cost of radiographic inspection prohibit its use for 100% inspection of heavy objects except when a service failure of the product would endanger the lives of individuals or associated expensive equipment. For other multi-ton castings and large, complex structural weldments, radiography should be considered as an aid to process control rather than as a method of final inspection.

Table VII. Discontinuities in Weldments Detectable by Radiography

Porosity
Slag
Cracks
Inadequate penetration
Incomplete fusion
Insufficient thickness
Undercuts
Burn-through
Inclusions
Segregation
Slugging
Bridging
Sputters

The successful application of radiography to mass product inspection is best illustrated by experience in the light alloy casting industry. Frequently, manufacturers of aluminum or magnesium castings must certify the quality of a large number of castings produced at a high rate. When many castings are made from the same pattern, jigs and fixtures will speed radiography by eliminating lifting, facilitating handling, and reducing film setting and blocking time. This permits the fullest utilization of the available x-ray beam. Rotating and tilting positioners, such as are employed for welding, have been found useful.

Most small castings are amenable to automation in radiography. Where large numbers of small parts are to be radiographed, a special lead-lined hood or cabinet, with mechanically operated lead-lined doors, electrically interlocked with the x-ray control, may expedite production. This type of equipment can be designed with roller-feed tables or loop conveyers, or both, upon which the next group of parts may be prepared for exposure. Some include power-driven traversing mechanism for the jigged parts, interlocked with the controls of the high-voltage circuit.

High rates of radiographic inspection usually depend on short exposure periods that require x-ray units of adequate capacity. Fast industrial x-ray film, a double-film technique or intensifying screen also help in reducing the exposure time.

Since, with normal technique, the various radioactive isotopes require long exposure periods, they have not been found useful for high-production inspection. Attempts to reduce the exposure time per casting have been made by increasing the quantities of the radioactive isotopes and by multiple exposures using the panoramic technique.

High production in the exposure room is of no value unless the film processing cycle can maintain the same rate. For the highest rates, automatic film processing machines are employed.

Industrial x-ray fluoroscopes have been designed for the inspection of light alloy castings, and a high rate of examination has been possible through the use of special conveyor systems.

Where cost is not a factor the highest and most efficient rates of mass radiography can be accomplished by designing a department for one specific application. For example, some of the highest radiographic production rates were reached during the last war in several U.S. Government shell loading plants.

Radiography of Weldments

In the inspection of weldments, radiography is an important tool for the location of internal discontinuities. It is the oldest and best known nondestructive means for this purpose. It is used to establish welding procedures, to qualify welders, to inspect welded fabrications in process and to control the quality of the product.

For routine inspection in the aircraft industry, weld test strips, made every hour on production welding, may be inspected by x-ray to supplement destructive tests where results are in doubt. When quality has been established, an occasional x-ray exposure can be made on every production run, and a metallographic test and some other suitable surface inspection method can be applied.

Much radiography of welded joints is subject to national codes (ASME, API-ASME, API-AGA), military and customer specifications, and recommendations of bodies such as ASTM, AWS, ASA and AEC, which control the radiographic procedures indirectly through specifying directly the minimum acceptable radiographic techniques.

Table VII lists discontinuities in weldments that may be revealed by both x-ray and gamma radiography. Except for cracks, the discontinuities are not cause for rejection until they exceed the maximum lengths or quantities acceptable in the particular fabrication being inspected.

When indications present in the weld are beyond the limits of acceptability, the defective area is plotted, and the weld machined, chipped or ground out (when permitted by specifications). Another radiographic inspection may be made to see if the defect has been removed. The undercut area is then repair welded and radiographed again to determine its acceptability.

Surface imperfections such as tool marks, sharp changes in section, even ripples in fusion weld beads can be confused as defects unless the interpreter is careful to evaluate properly. An inspector must be able to distinguish between images of weld surface irregularities and those of welding defects, and also to evaluate surface indications as to acceptability in the particular structure in question.

Specifications usually limit radiographic procedures with the following minimum conditions:

1. D/t ratio to be not less than 7/1. (D/t is the ratio of the distance from source to specimen to the distance from radiation side of specimen to film).
2. Film should be as close to the specimen as possible and never farther than 1 in.
3. Variation in thickness of specimen within a single-film radiograph to be not more than 12½%.
4. Maximum area covered by a single film should be limited by points where the radiation must penetrate a thickness exceeding that penetrated at the center of the film area by 12½%.
5. Penetrameter to be placed at the outer edge of the film area, that is, at the location representing the greatest angle with the axis of radiation
6. Image of the smallest hole of the penetrameter must be visible on the finished radiograph.
7. Radiographs should indicate that defects as large as 2% of the thickness of the part being examined, or larger, will be resolved.
8. The weld being examined should be free from surface irregularities that could mask defects within the welded area.
9. Films must be free from processing and mechanical defects.
10. Each film should bear the image of the job number, the weld number, and the film location number, which should be established permanently on the part being inspected.
11. High-speed, coarse-grain films are not acceptable.
12. (*a*) Film densities of 1.5 to 2.5 are acceptable for high-contrast, fine-grain films, used with or without lead screens. (*b*) Film densities of 1.0 to 1.5 are acceptable for the fluorescent-screen type of films.

Limitations. One of the chief limitations of the radiographic process is that relating to detection of cracks. To be recorded they must be in or near a plane parallel to the direction of radiation. The majority of cracks in fusion butt welds will fall in a plane at or near the plane of radiation normally used for butt welds. It may be necessary and justifiable in suspicious or critical areas to radiograph the part at different angles to reveal cracks that do not fall close enough to the original plane of radiation to be detected.

The minimum size of defects that can be shown by conventional radiography is also a limiting factor. Radiography should not be expected to reveal flaws or irregularities that are microscopic or to disclose information regarding metallurgical structure or physical properties. The primary function of radiography is to reveal flaws or discontinuities that may be attributed to poor workmanship or poorly operating welding equipment and will be detrimental in further processing or in the service life of the part.

Various unusual arrangements are frequently employed to facilitate and improve interpretation of radiographs. Among them are:

1. Two films in a cassette—one fast and one slow—to provide similar sensitivity and density for wide variations in specimen thickness
2. Radiographically dense fluids, plastics, or metallic powder or shot to equalize irregular thickness of section
3. Double-film exposure technique, to reduce exposure time
4. A fixer neutralizer to decrease film-processing time and insure storage life.

5 Double images to provide a depth-locating measurement for defects. Stereoradiography may also be used.
6 Lead filters (0.010, 0.020, 0.040 and 0.060 in. thick) at the front side of the cassette to improve contrast for the fluorescent-screen type of films, starting at 1.5-in. specimen thicknesses.

Radiography of Aluminum Weldments

Radiographic technique and equipment for examining welds in aluminum and magnesium alloys are no different from methods used for parts that are not welded. The discontinuities produced by fusion welding of aluminum and revealed on film by radiography are included in Table VII.

A special exposure technique is necessary for the inspection of spot welds. The welded areas are x-rayed with a low-voltage, high-intensity, beryllium-window x-ray tube on extremely fine-grain film. Spot welds and seam welds produce x-ray images of aluminum and its alloys that are entirely different from those of any other welding technique. Because of the rather large percentage of radiographically dense alloying constituents that produce informative patterns, some of the high-strength aluminum alloys such as 2024 and 7075 are well suited for spotweld radiography. The images show positive indications of the following:

1 Variations in weld nugget shape (oversize, undersize, absence, misshapen, doughnut and crescent-shaped)
2 Extrusion and expulsion of metal from the nugget
3 Cracks
4 Porosity
5 Foreign materials (such as tip pickup)
6 Segregation of eutectic
7 Electrode impressions

However, not all aluminum alloys will provide informative spot-weld radiographs, for example, alloys 1100 and 3003.

If incomplete fusion at an interface between weld and parent metal is suspected, additional exposures at various angles may reveal the lack of bonding.

Because of low subject contrast, it is difficult to obtain the necessary sensitivity with radioactive sources.

Radiography of Iron and Steel Castings

Radiography is in widespread use for nondestructive inspection of iron and steel castings. For some castings, two or more nondestructive test methods must be used in order to get the desired information.

Since gamma rays radiate in all directions, a number of exposures can be made at one time by grouping the castings around a radioactive source in a panoramic arrangement. Another advantage in the use of radium or radioactive isotopes is in the flexibility of the equipment. The source is easily transported and used in the shop, and inspection of internal passages and cored openings is possible. The chief disadvantages of these methods, as compared with x-rays, are the increased exposure time and the poorer contrast of the radiograph.

X-ray machines from 200 to 400 kv are common in foundry work. The 1000 and 2000-kv x-ray machines and industrial betatrons are used for heavy-section work. Discontinuities that may be detected by radiography are listed in Table VIII.

If areas of internal shrinkage or other discontinuities are found that are undesirable, satisfactory repair can usually be made. If the area is really critical, radiography may be used to check the removal of the defect and again to prove the soundness of the repair weld. On viewing the radiograph it is often difficult to determine whether an internal defect can be removed better from one side or the other (assuming the casting is of such a nature that the repair can be made from either side).

Table VIII. Discontinuities in Iron and Steel Castings Detectable by Radiography

Shrinkage
Gas porosity
Inclusions
Hot tears
Cold cracks
Cold shuts
Misruns
Unfused chaplets and chills
Core shift
Surface irregularities

The radiographic inspection should be made in the steel foundry itself and preferably during or immediately following the cleaning operation. The casting must be clean enough so that good work is possible and any shadows produced on the radiograph will be significant. Any surface condition that will be seen on the radiograph should be indicated by the use of a small lead arrow placed at this location on the casting and later visible on the radiograph, to inform the interpreter that the discontinuity shown on the film is a surface condition.

The advantage of radiographing the casting during the cleaning operation is that all repair welding can be done at the same time. This is especially important for alloy steel castings that require preheat and postheat for obtaining welds of the best quality.

Radiography of Aluminum and Magnesium Castings

Although a large percentage of light alloy castings can be radiographed satisfactorily with 250-kv x-ray equipment, low-voltage units, 150 kv or less, will give the highest efficiency for sections as thick as 2 in. The size and distribution of discontinuities commonly encountered require the use of x-ray tubes that have a relatively small focal spot and low inherent filtration to get a high radiographic sensitivity.

Correct radiographic procedure is to select the lowest voltage that will do the job in a reasonable exposure time. Where many castings are examined a convenient technique is to establish a reasonable exposure time and select the voltage required for the thickness of the particular section being radiographed. Good practice normally requires exposures of not less than 1 min.

When castings with great differences in thickness must be radiographed in one exposure, an increase in voltage will provide wider latitude, as well as shorter exposure time, but with reduced contrast. If other factors remain constant, the most desirable combinations of voltage and exposure time for a specific part being examined may be governed largely by the minimum acceptable radiographic sensitivity.

Although the discontinuities commonly encountered in aluminum and magnesium castings are similar to those in ferrous metals, frequently a group of irregularities called "dispersed defects" may be present. These defects, prevalent in light alloy castings, consist of tiny voids scattered throughout part or all of a casting. Gas porosity and shrinkage porosity in aluminum alloys are examples of dispersed defects.

On radiographs of sections more than ½ in. thick it is difficult to distinguish images corresponding to the individual voids. Instead, dispersed defects may appear on film deceptively as mottling, dark streaks or other irregularities.

The discontinuities that can be detected by radiography of light alloy castings are listed in Table IX.

Radiography for Maintenance Inspection

Radiography is used for maintenance inspection to determine changes in the product through use or to determine the quality of repair operations. In general, it is assumed that manufacturing defects, such as porosity and inclusions in castings and weldments, are detected in the normal manufacturing inspection procedures. Maintenance inspection would not be used for these types of defects.

Table IX. Discontinuities in Aluminum and Magnesium Castings Detectable by Radiography

Hot cracks
Cold cracks
Cold shuts
Shrinkage cavities
Misruns
Gas holes
Gas porosity
Dross or slag inclusions
Segregation
Core shift
Mottling from large grain sizes
Surface irregularities
Microshrinkage
Hydrogen porosity (Al)
Shrinkage and sponge (Al)
Microporosity (Mg)

Changes caused by fatigue but not associated with actual discontinuities in the metal are not readily detected by radiography. It is common practice in aircraft maintenance to inspect by radiography structural parts that are normally under cover of the fuselage and not visible to inspectors. Radiography allows an inspection, without removing the aircraft aluminum skin, for such defects as possible cracks or fractures caused in structural members by unusual operating conditions of the aircraft.

Radiography has been used in maintenance and repair of naval ships and railroad equipment for certain applications. It is used to inspect die blocks for dimensional changes and to measure elongation of rivets and structures where these parts are easily accessible to radiographic equipment.

Other maintenance inspections are made by radiography of products in which normal use causes dimensional changes. Melting pots used in the magnesium foundry are an example. When the bottoms become thin, they are replaced, thereby preventing failure.

Radiography for Inspection of Finished Assemblies

X-ray inspection is used to check electrical connections and precision parts in aircraft assemblies, and the position of bolts and nuts in finished enclosures. Even the dimensions of some components have been measured with acceptable accuracy.

Holes drilled off location on finished assemblies have been repair welded, redrilled in the proper locations for structural fit-up and subjected to x-ray examination. Small bosses and pads have been removed, repositioned and rewelded for fit-up and then x-rayed again to check quality. When thousands of dollars are invested in such products, an x-ray inspection is essential to assure the soundness of repairs.

Meters, timing mechanisms, electronic tubes of all kinds, fuses, electrical switches and small electric motors are checked for position of parts and completeness of the assembly. Ammunition fuses housed in metal cases are inspected on a routine production basis to make certain that components are properly installed.

The amount of insulation around metal wire on fuel pumps immersed in gasoline can be checked to prevent a fire hazard. Where failure would be dangerous or expensive, 100% inspection is often justified and required.

The height of liquids or solids can be determined and solution percentages in closed vessels can be evaluated. When it is too costly or time-consuming to disassemble the finished product, x-ray inspection may be used.

Radiography of Powder Metal Parts

Sintered compacts are sometimes infiltrated with other metals to increase strength. An outstanding production example is iron infiltrated with copper. Radiography is the only feasible method for detecting uninfiltrated regions and the size, location and distribution of porosity and cracks.

Defective parts are subjected to tensile, fatigue, and other destructive tests, and a direct correlation can be made as an aid in setting up radiographic inspection standards. Parts similar to the ones accepted by mechanical testing can be used to make up suitable penetrameters. A flat-bottom hole is drilled into the thickest section of the part to a depth equivalent to a certain percentage of this thickness.

The major cause for rejection of infiltrated iron powder parts is failure of the copper to fill voids between the metal particles. Common practice has been to reinfiltrate the part with more copper. This gives almost 100% recovery on the second x-ray inspection.

Radiographic inspection has also revealed subsurface cracks caused during broaching and other machining.

Microradiography

The microradiographic technique may be used to detect minute discontinuities in metals or segregation of components in alloys. It involves the radiography of a thin specimen on a fine-grain photographic material. The resulting radiograph is then examined under a magnification that may be as high as a few hundred diameters. Since microradiography of metals often involves sectioning a specimen, it is not usually a nondestructive test.

Metal samples for microradiography range from 0.001 to 0.020 in. thick; the exact thickness required depends on the composition of the metal and the purpose of the investigation. Some specimens prepared in this way may be radiographed without further preparation—for example, in the microradiography of light alloys to disclose minute discontinuities. For determination of segregation of constituents in light alloys and for all examinations of ferrous and copper alloys, thinner specimens than can be produced by a cutoff saw are usually needed. Indeed, a wedge-shaped specimen is often an advantage, since the radiographic exposure will be less critical when a range of densities from one end of the specimen to the other is to be obtained.

Table X. Photographic Materials for Microradiography

Material	Approx Relative Speed	Approx Max Enlargement, diam
Lowest-graininess, highest-contrast type of industrial film	100	12
Fine-grain spectroscopic plate	40	35
Fine-grain positive film	7	75
Extremely high resolution plate (Lippman type)	0.2	400

Technique. Low voltages, in the range from 10 to 50 kv, are required in microradiography because of the thinness of the specimen and the need for high contrast in the finished microradiograph. Both the continuous, or "white", x-radiation and the characteristic K-spectrum from a suitable target find use in microradiography. The continuous spectrum can be used for detection of minute discontinuities, or of segregation in alloys in which the components are widely different in atomic number, as in aluminum-copper alloys, or in the determination of the dispersion of lead in a leaded brass. For such applications, tubes with a tungsten target and beryllium window are useful, operating up to 50 kv. The continuous spectrum from x-ray diffraction tubes can also be used. The white radiation from ordinary industrial radiographic tubes operated at a low voltage has been used successfully in microradiography, although the x-ray intensity obtained at low voltages is severely limited by the thickness of the tube window. Where a segregation of components that do not differ greatly in atomic number must be detected, use of the characteristic K-spectrum from a suitably chosen element gives best results.

Since microradiographs must be enlarged for interpretation, a fine-grain photographic film or plate is needed. Table X gives approximate speeds and maximum enlargements.

Many of the photographic films or plates used for microradiography can be developed for 5 min in conventional x-ray developers. Special precautions are necessary only with films of extremely high resolution, which should be processed as soon as possible after exposure. Fading of the latent image has been observed, and storage overnight may cause appreciable loss in the density of the developed image. In addition, the use of a stop bath (3% acetic acid) between developer and fixer is especially important in the processing of high-resolution photographic materials.

Extremely good contact between specimen and film is necessary for achieving the maximum enlargement of which the film is capable. Good contact may be obtained with a simple mechanical jig that presses the specimen against the film or plate, but best results will probably be obtained with a vacuum exposure holder.

Any material placed between tube and specimen must be thin and of low atomic number (for example, thin cellulose sheet) to reduce x-ray absorption to a minimum, and must have no marked structure.

Stereoscopic microradiographs may be made by moving the tube or moving or tilting the specimen between successive exposures.

It is hardly practicable to specify exact exposure techniques in microradiography, but the following example may serve as a useful guide: specimen, aluminum alloy 0.010 in. thick; exposure, 20 kv, 25 ma; 12-in. focus-to-film distance; time, 4 min; film, fine-grain positive film.

Because of the relatively high absorption by air of the very soft x-radiation used in microradiography, the x-ray intensity will decrease with distance from the focal spot more rapidly than calculations based on the inverse square law would indicate.

Viewing of Microradiographs. If simple visual inspection with a hand magnifier or microscope will not suffice, photographic enlargements of microradiographs must be made. Enlargements in the form of transparencies on film are preferable to paper prints.

If photomicrographic equipment is not available, enlargements up to about 40 diam may be made with a photographic enlarger. A microfilm enlarger embodying a "point source" and condenser illumination is to be preferred, although any photographic enlarger of good quality may be used.

If photomicrographic equipment for transmission specimens is available, it is preferred for enlarging microradiographs. Such micrographs, up to magnifications of about 100 diam, can be made quite readily in most metallographic laboratories. If enlargements of several hundred diameters are needed, equipment for transmission photomicrography is required.

In general, higher contrasts (up to gamma of 2.0) will be used for film enlargements with specimens of lower *radiographic* contrast. A slow film will often have the advantage of giving exposure times long enough to be timed easily, particularly if the work is done with a photographic enlarger. If the enlargement is to be viewed directly, a matte-base film can be used, or the enlarged microradiograph can be contact printed on film with a clear or a matte base, or on paper.

References on Microradiography

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H. R. Splettstosser and H. E. Seemann, "Application of Fluorescent X-Rays to Metallurgical Microradiography", J Appl Phys (Nov 1952)

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Macro-Etching of Iron and Steel

By the ASM Committee on Macro-Etching

MACRO-ETCHING of iron and steel is an inspection procedure for revealing certain aspects of quality and structure of the metal by subjecting it to the action of a corrosive reagent and examining it visually or at low magnification.

Macro-etching is widely used for the inspection of bars, billets, forgings, castings and other iron and steel products. Samples are usually selected to represent a given batch or lot of metal and destructively tested by etching in acid until the structural characteristics or conditions are revealed. Some bars or forgings that are to be further worked or machined are inspected nondestructively by this method. Macro-etching may be used to reveal bursts, pipe, segregation, overheating, cracks, porosity, nonmetallic inclusions, seams, grain flow, macro grain size, decarburization, local or surface hardening, grinding burns and weld penetration.

Selection of Sample. The sample will usually consist of a full section of material and should be thick enough to permit easy handling and subsequent surface preparation. The maximum size of sample will be governed by the available macro-etching facilities.

Transverse or cross-sectional samples are most common. When longitudinal samples are taken to indicate the effect of structural elongation by rolling or forging, the section should be cut parallel to the direction of metal flow and preferably through the center line of the piece.

Where surface inspection is the principal consideration, the article itself may serve as a suitable sample. In surface inspection for seams and laps, the sample consists of sections selected at random.

Consideration should be given to the stage of forming at which the sample is selected. Macro-etching exaggerates inhomogeneities; therefore, conditions that might be detrimental in a completely formed steel, would not necessarily be a matter for serious consideration when the metal is to be worked subsequently.

Preparation of Sample. A sample of soft metal for macro-etching can be taken from the whole by either sawing or machining; hardened steel requires abrasive cutting. Flame cutting may be convenient for obtaining samples from very large sections. All traces of burning or tempering must be removed before etching. It is also desirable to remove oil, grease and dirt with some suitable solvent. This will produce better results and prevent excessive contamination of the etching solution.

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The surface finish required before etching depends to a great extent on the action of the etching solution; in general, the more drastic the action of the reagent, the coarser the surface finish may be. A smooth sawed or machined surface is usually adequate, though grinding and polishing are sometimes required to produce finer detail. When inspection for surface imperfections such as seams, laps or checks is the primary purpose, no special preparation is required, as the etchant will remove rust and scale.

Equipment for Macro-Etching

The principal equipment is a container for the etchant, provision for heating the etchant if necessary, a ventilating system to contain and carry away corrosive fumes, and some means for washing and drying the sample.

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For occasional work with small samples, equipment available in most analytical chemical laboratories is adequate — a glass tray on a hot plate under a hood. For production etching, however, equipment is needed that will give satisfactory service over a long period, and hoists or conveyer systems are commonly used to minimize handling problems. The installation should have a covering hood equipped with a forced exhaust system to remove the corrosive fumes. A spray nozzle or shower head should be located near the etch tank as a safety measure for use if a worker gets acid on himself.

Etch Tanks. Dishes or trays made of porcelain, pyrex glass or corrosion-resistant alloy can be used. For large production installations, three types of construction are most common: (1) tanks molded from a mixture of special acid-digested asbestos or graphite filler and synthetic resin; (2) steel tanks coated with rubber or synthetic resin and lined with properly bonded acid-resistant brick or carbon brick; and (3) corrosion-resistant metal. Nonmetallic construction is more common than metal. When metal is used, lead is most common for resisting sulfuric acid solutions, and high-nickel alloy or high-silicon iron for muriatic acid (HCl). For resisting sulfuric or muriatic acid, or both, a nickel-molybdenum-base alloy can be used.

Rinse Tanks can be of the same material and interchangeable with etch tanks, or of stoneware or other ceramic material.

Neutralizing Bath Tanks. A neutralizing solution such as dilute ammonium hydroxide, when used, can be held safely in a container made of carbon steel sheet.

Hood and Exhaust System. The hood and exhaust system can be of treated wood, molded asbestos, plastic or steel coated with acid-resistant synthetic resin. The exhaust system preferably consists of a blower to raise the room pressure and, adjacent to the stack, another blower that delivers air into the stack to exhaust the fumes collected under the hood.

Heating Equipment. Trays may be heated by a gas or electric hot plate or a steam jacket. Large tanks can be heated by a low-pressure steam heat exchanger made of corrosion-resistant alloy or graphite, or by a steam jet discharging directly into the etching solution. The method of heating that is

Supersedes the article on page 389 of the 1948 ASM Metals Handbook.

Table I. Etching Solutions and Recommendations for Production-Control Macro-Etching of Steel

Solution	Bath Composition[a]	Temp, °F[b]	Time[b]	Surface[c]	Purpose, or Characteristic Revealed
		For Carbon and Alloy Steels			
HCl	50% in water (muriatic or CP)	160 to 180	15 to 60 min	A or B	Segregation, porosity, cracks, inclusions, dendrites, flow lines, hardness penetration, soft spots, structure, and weld examination
	Undiluted acid	160 to 180	15 to 60 min	A or B	
$HCl + H_2SO_4$	2 parts sulfuric acid 1 part muriatic acid 3 parts water	160 to 180	30 to 60 min	A	Same as above
	80 parts muriatic acid 7 parts sulfuric acid 18 parts water	160 to 180	30 to 60 min	A	Same as above
H_2SO_4	10 to 25% in water	Room	8 to 24 hr	B	Same as above
HNO_3	2 to 25% in water or alcohol	Room	5 to 30 min	B or C	Carburization and decarburization, hardness penetration, cracks, segregation and weld examination
		For Stainless Steels[d]			
HCl	Undiluted acid (muriatic or CP)	160 to 180	20 to 60 min	A or B	Segregation, porosity, cracks, inclusions, dendrites, flow lines, structure, and weld examination of 400 series and all of 300 series except those listed below
		160 to 180	½ to 4 hr	A or B	Same for types 310, 316, 316L, 317 and 330
	50% in water	160 to 180	20 to 60 min	A or B	Same for 400 series and all of 300 series except those listed below
		160 to 180	½ to 6 hr	A or B	Same for types 310, 316, 316L, 317 and 330
$FeCl_3 + HCl$	65 g ferric chloride 195 ml muriatic acid 5 ml nitric acid	130 to 160	10 to 20 min	A or B	Same for various stainless steels

(a) All acids of concentrated strength; "parts" are by volume. Water or alcohol should never be poured into an acid; rather the acid should always be poured into the other liquid. (b) See text for discussion of variations. (c) Surface A means a saw-cut or machined surface; surface B, an average ground surface; surface C, a polished surface. (d) After macro-etching, the 300 series stainless steels should be rinsed with 10 to 30% nitric acid to whiten the surfaces.

most adaptable or can be controlled most effectively in the particular equipment is usually selected.

Temperature Control. Temperature is usually measured by a mercury thermometer and the heat source controlled manually.

Plumbing. The necessary piping and fittings can be made from ceramics, plastics or alloys, as indicated for the other acid-resistant equipment.

Acid Disposal. Where large volumes of acid are being disposed of, the same precautions apply as for the handling of pickling solutions.

Etching Solutions

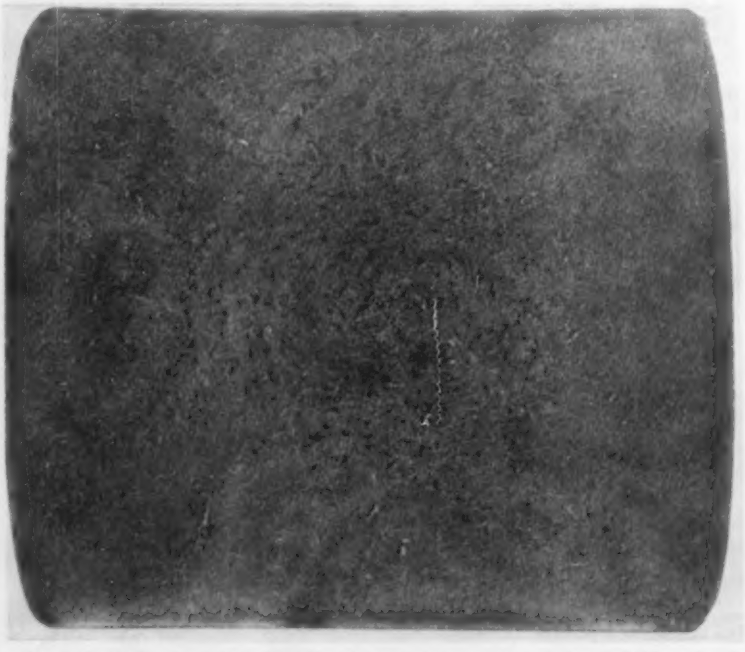
A 50% solution composed of one part of muriatic acid (the commercial grade of hydrochloric acid) and one part of water is recommended for the general macro-etching of carbon and alloy steels. However, undiluted hydrochloric acid (either muriatic or CP grade) is more effective in etching the lower-carbon, more highly alloyed constructional steels, such as 2512, 9310 and 4320. The undiluted hydrochloric acid solution may also be used as a general etchant for stainless steels of the 300 and 400 series. Carbon and alloy steels of medium to high carbon content can be etched in the 50% muriatic acid solution with excellent results.

Another etching solution recommended for general macro-etching of carbon and alloy steels is composed of two parts of sulfuric acid, one part of muriatic acid and three parts of water.

To develop the general macrostructure, stainless and heat-resisting steels may be etched in a solution of muriatic acid (195 ml), ferric chloride (65 g) and nitric acid (5 ml) at a temperature of 130 to 160 F, with the advantage of a shorter etching time than for undiluted muriatic acid at 160 to 180 F.

Table I gives recommendations for production macro-etching of carbon, alloy and stainless steels. For routine inspection, it is unnecessary to dispose of the etching solution after each test, but for best results a fresh solution should be used for each test or group of tests. With stainless steels, spurious pitting effects may be obtained when using muriatic acid (HCl) contaminated by iron, particularly when certain stainless grades (notably 403 and 410) are etched below the recommended temperature.

Temperature of Acid. For most of the reagents used above room temper-



Alloy Steel Billet Section (Originally 9 by 9 In.) Representing Product from Top Location in Ingot. Normal segregate or "carbon spots" and dendritic macrostructure. Macro-etched in 50% HCl at 160 to 180 F

Table II. Principal Macro-Etch Observations to Be Recorded for Semifinished Steel Products

Surface or Subsurface	Center or Central Area	General
(A) Cracks	(a) Pipe	(α) Flakes or cooling cracks
(B) Seams or laps	(b) Porosity	(β) Dendritic pattern
(C) Decarburization	(c) Bursts	(γ) Ingot pattern
(D) Pinholes	(d) Segregations	(δ) Grain size
(E) Segregations		

ature, an etching temperature of 160 to 180 F is recommended in Table I. At a temperature on the lower side of this range, the etching reaction should be sufficiently vigorous so that the solution will not evaporate too rapidly for economical control. However, in production-control etching, the higher temperature is preferred because it decreases the duration of etching.

Etching Procedure

The most common procedure is to put the prepared specimens directly into the heated solution, with the surface to be examined either face up or vertical to permit the gas generated during etching to escape freely. Nonuniform etching will result if the specimens overlap or if they are racked too close together. Large billet or bloom sections require a long period to reach the temperature of the etching solution. For maximum uniformity or where a large volume of samples are to be etched in a relatively small volume of acid, it is advisable to preheat the samples in a water bath to the same temperature as the etching solution. This permits more precise control of etching time and simplifies control of solution temperature.

Duration of Etching depends on the type of steel, surface condition and physical condition of the sample. For best reproducibility of results with a large number of samples, the time should be measured and should not vary from batch to batch. Unless the sample is etched long enough, it will not reveal all the information desired; if etching continues too long, some of the more delicate details of structure will be masked or obliterated by the general destruction of the surface.

The durations of etching recommended in Table I are for average results on annealed specimens. The time actually required to develop the desired results in a particular test can be determined by examining the sample frequently as etching proceeds. Marked variations in the susceptibility to attack by the acid solution will be found among different heats of steel and with different methods of heat treatment. Susceptibility to attack also varies with the position of the sample in the ingot (which determines the amount of segregation) and with the machined finish of the surface. Resulfurized steels of the carbon, alloy and stainless grades usually etch very rapidly. Some austenitic stainless grades, especially those containing molybdenum, may require etching for several hours when undiluted muriatic acid only is used to develop the macrostructure.

Preservation of the Sample. After the sample has been properly etched, it should be removed from the hot acid and washed thoroughly under running water, then scrubbed with a stiff fiber brush to remove the deposit of "smut" from the surface, rinsed again and dried by air blast or by blotting with paper or cloth towels. Immersion in the acid for a few minutes after scrubbing results in better definition, especially for flow lines.

As a temporary means of avoiding rust, the etched specimen may be rinsed in water, dipped in a dilute alkaline solution (such as aqueous ammonium hydroxide) to neutralize the remaining traces of acid, and washed in hot water. For longer preservation, the dried specimen should be covered with a thin film of transparent plastic, clear lacquer or oil. The spray-type packaged plastics provide the most convenient method of applying this protective film. The plastic, lacquer or oil should be removed when the macro-etched specimen is to be studied further.

Rusting can be delayed temporarily and some rust may be removed from dried specimens by application of a 50-50 solution of phosphoric acid and water. The excess solution may be blotted up with cloth or paper towels. Caution is recommended in the use of this technique because the strong acid solution will roughen the hands and disintegrate cloth if allowed to remain in contact for an extended time.

Recording of Results

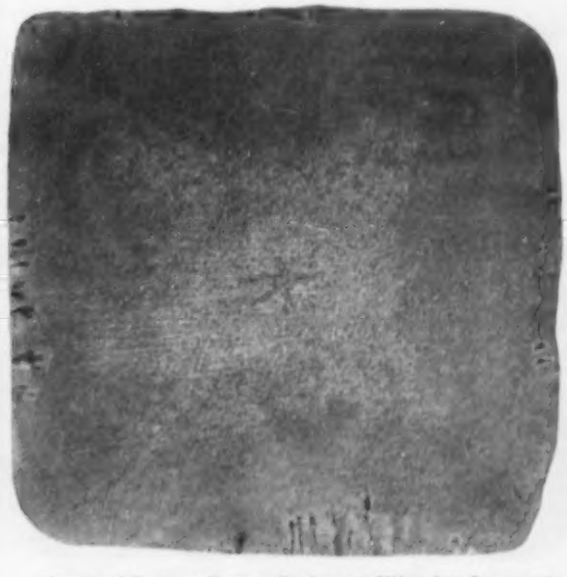
In recording the results of macro-etch inspection, the observed conditions may be grouped according to type and location. The record should include full information as to the type and composition of the steel, the cross-sectional dimensions and a description of the conditions or defects observed.

Table II gives a suggested check list for use in recording macro-etch observations. The defects or conditions may be further coded to indicate degrees of severity and applicability to particular parts or uses.

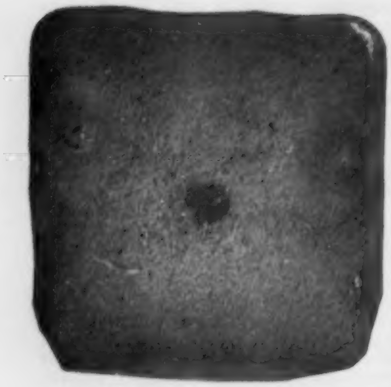
Interpretation of Results

The results obtained on properly etched specimens are of great value if interpreted correctly. Surface seams, internal cracks and pipe are easily recognized. Incorrect interpretation of the evidences of segregation and dendritic structure, as revealed by macro-etching, may cause expensive errors and needless rejection of metal. For instance, every pit does not indicate an inclusion or evidence of an undesirable condition, since pitting may result from

Internal Cracks (Thermal Flakes) in Alloy Steel. 5/6 size. Etched in 50% HCl at 160 to 180 F



Very Bad Surface Seams. Center condition barely acceptable. Carbon steel. 5/6 size. Etched 50% HCl, 160 to 180 F



Slag Inclusions (White) and Porosity in Carbon Steel. ½ size. Etched in 50% HCl at 160 to 180 F

the use of partially spent acid or from attack around normal carbide particles. Irregular etching effects, such as blotchiness or pitting, may be obtained if the surface being etched has retained oil or grease, was smeared or cold worked in machining, was protected from the etchant by contact with other specimens in the bath, or if the etching solution was dirty or contaminated.

Macro-etch results can be interpreted only in terms of the type and grade of steel being inspected. Rimmed, semikilled and killed steels will exhibit characteristics of the manufacturing methods. Poor control of either bath temperature or duration of etching will greatly affect the characteristics of the etched surfaces. When questionable results are obtained, it is good practice to remachine the surface and etch in a fresh solution under carefully controlled conditions.

Most of the conditions that are described below are illustrated by the accompanying macrographs.

Cracks from Etching. Before etching, hardened or otherwise highly stressed steels should be tempered sufficiently to prevent cracking since, without this precaution, sound steel may crack in the etching solution and thus lead to false conclusions.

Grinding Cracks can be distinguished easily in a short-time macro-etch test and are usually, but not always, identified by a pattern of some symmetry. Again it must be emphasized that hardened pieces should be softened by tempering before hot etching.

Surface Cracks. As revealed by macro-etching, surface cracks usually follow an irregular path and may result from wrong handling during heating, forging, rolling or cooling from finishing temperature. On heat treated steel, surface cracks may be caused by incorrect treatment, improper grinding, surface decarburization or surface stresses.

Seams and Laps in rolled steel are of varying depth and usually extend in a straight path parallel to the direction of rolling. In forged steel, seams generally follow the contour of the forging and the flow of the metal.

Center Porosity. If porosity at the center is the result of an actual discontinuity within the metal, it may be evident before etching. Usually, however, the porosity is not evident until the metal has been etched. This condition may be found in widely varying degrees, and the interpretation of its relation to quality should include consideration of the grade of steel and cross-sectional dimensions of the product represented. For example, the conditions observed in a 12 by 12-in. bloom may be more pronounced than in small sections.

Pipe and Bursts. Pipe is an internal shrinkage cavity formed during solidification of ingots of fully deoxidized steel. It may be carried through the various manufacturing processes to the finished product. Pipe is invariably associated with segregated impurities, which are deeply attacked by the etching reagent. Cavities in the center that are not associated with deeply etched impurities are often mistaken for pipe, but such cavities can usually be traced to bursts caused by incorrect processing of the steel during forging or rolling. Either pipe or bursts should be visible after deep etching; they can generally be distinguished from each other by the degree of sponginess surrounding the defect. Piped metal usually shows considerably more sponginess than burst metal.

Nonmetallic Inclusions, Metallic Segregations and Pinholes. Although nonmetallic inclusions usually appear as pits or pinholes, they must not be confused with pits that result from etching out metallic segregations or from variations in etching procedure. When nonmetallic inclusions are suspected in highly alloyed steels that may contain metallic segregations, a comparison should be made of an annealed specimen and a hardened and tempered specimen etched in the same way. If the etching pits are the result of nonmetallic inclusions, they will appear similar in both the annealed and the hardened specimens. If they are the result of metallic segregation, they will differ in appearance.

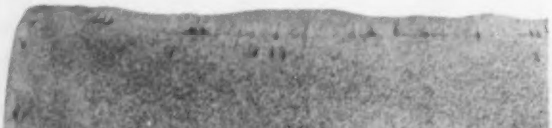
Although macro-etching may furnish a good indication of the cleanliness of the steel, it is preferable to make research studies by metallography if information is desired regarding the character of nonmetallic inclusions that may be present.

Segregations are revealed by differences in the severity of the acid attack on the affected areas. Segregations at the center may be attacked so deeply after etching that they appear as a pipe, or the segregations may be grouped in some fairly regular form about the center, depending on the shape of the ingot and the mechanical work done on it.

Segregation, as revealed by macro-etching, is not always an indication of defective metal. A polished specimen should be examined under the microscope to determine whether the revealed segregation is metallic or a concentration of impurities. The microscopic identification of segregation may be supplemented by chemical or other means of testing.

Internal Cracks, sometimes called "flakes", "cooling cracks" or "thermal cracks", can be detected by the macro-etch test, and their identity can be verified by a fracture test of a hardened specimen in which the cracks are re-

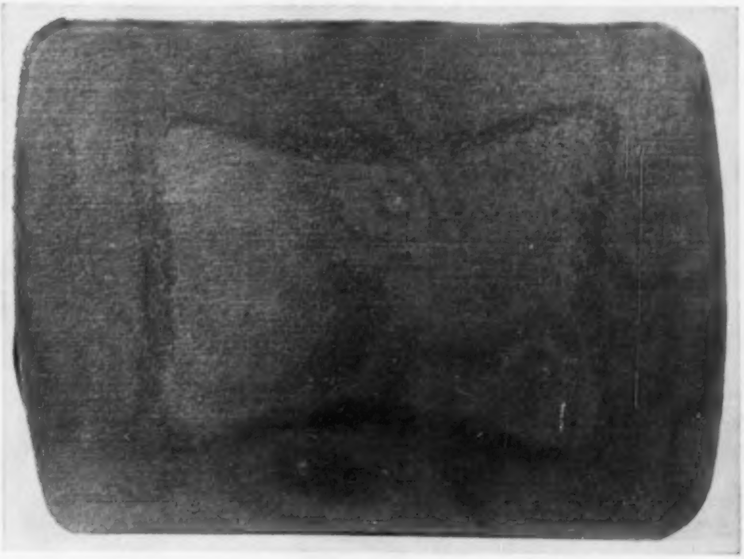
Pipe Defect in Billet Product Representing Top Portion of Ingot. Macro-etched in 50% HCl at 160 to 180 F



Pin Holes and Subsurface Porosity in Billet; Bottom Location in Ingot. Macro-etched in 50% HCl, 160 to 180 F vealed as bright crystalline spots.

Dendritic Structure. Etching often reveals a dendritic structure that results from the crystalline characteristics of the ingot. Dendritic structure is detected even in steel that has been subjected to repeated mechanical reduction. This is not detrimental, provided the steel has been worked enough and provided the segregation accompanying the dendritic structure is not in the form of nonmetallic inclusions.

Ingot Pattern. The conditions leading to the formation of ingot pattern develop during solidification of the ingot. The pattern appears as a zone of demarcation between the columnar and heterogeneous regions of ingot solidification, which may persist during reduction of the ingot to billets and bars. Because inclusion material, particularly sulfides, may segregate to a minor degree in this region, macro-etching may reveal the presence of ingot pattern through preferential etching effects. In the absence of large amounts of sulfide and silicate inclusions, ingot pattern is of no serious consequence.



Ingot Pattern in Low-Carbon Alloy Steel. 3/5 size. Etched in 50% HCl

Grain Size. Macro-etching can be used to reveal areas of excessive grain size in some highly alloyed steels. It is not used for routine determination of grain size in the standard carbon and alloy steels.

Decarburization and Carburization. Ordinarily areas that have been either decarburized or carburized etch differently from the remainder of the specimen. The chief difference is in color: decarburized parts appear lighter and carburized parts darker.

If the section to be examined is small enough, it can be given a metallographic polish and can then be etched cold for 5 to 30 sec in nital (3% nitric acid, 97% alcohol). This will usually result in excellent contrast and, if the polish is good enough, the same specimen can be examined microscopically as well as visually.

Special Techniques

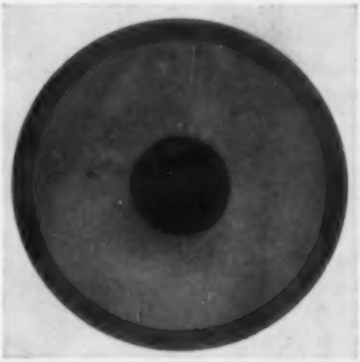
In addition to the routine use of macro-etching as a guide to quality control of semifinished steel in production, several more specialized uses of macro-etching methods are common, as indicated in the following discussion of specific conditions.

Overheating of Steel. Overheated steel forgings will display a network structure on the as-forged surface resembling fine chicken wire when etched in 1 part muriatic acid to 1 part water at 160 to 180 F. For best results the forgings should not be cleaned by shot, grit or sandblasting before etching. Results should be verified by examining a fractured section for facets after normalizing, quenching and tempering.

Flow Lines, indicating the direction in which the steel was hot worked, have become a part of the engineering specifications for certain designs of forgings and other parts—especially for aircraft engine components. The longitudinal face on which the flow lines are to be developed should have a smooth ground surface. Best results are obtained by using a fresh solution of 1 part muriatic acid to 1 part water at 160 to 180 F.

Temperature must be closely controlled because too violent attack will pit and roughen the ground surface so severely that flow lines may become obliterated.

The specimen should be removed from the bath frequently to observe the progress of etching. The usual practice is to scrub the etched surface with a brush or cloth under running water to remove the smut produced by the etching action; however, the flow lines sometimes show more clearly if the smut is left on.



Induction Hardened Case on a Forged Camshaft of 5046 Alloy Steel. ½ size. Etched in 15% ammonium persulfate in water

A 10 to 12% solution of ammonium persulfate at room temperature is also used for revealing flow lines.

Difference in Structure can be revealed on a smoothly ground surface by use of a fresh solution of 10 to 20% ammonium persulfate in water at room temperature.

A light scrubbing action with a cotton swab soaked with the etching solution gives the best contrast and will reveal: the zone produced by induction hardening, flame hardening or carburizing; the grain size and structure in welded sections; decarburized areas; and qualitative ferritic grain size in normalized steel forgings.

Tempering from Grinding or Soft Spots from Inadequate Quenching can be revealed on a smoothly ground surface by a two-solution sequence:

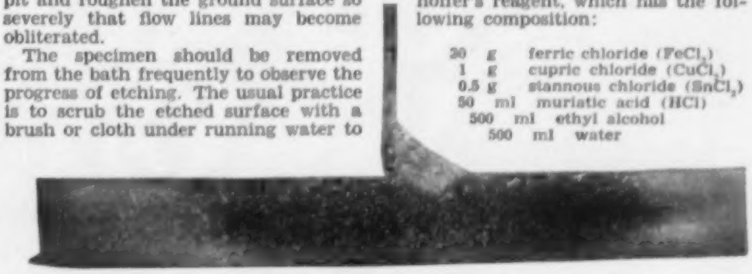
1 5% nitric acid (conc) in water
2 50% hydrochloric acid (conc) in water

The specimen is first washed in hot water, then etched in solution 1 until black; washed in hot water, immersed in solution 2 for 3 sec; washed in hot water and dried in an air blast.

The presence of lighter or darker areas indicates that structure and hardness have been altered in grinding. Soft spots, which often result during the hardening of carbon or low-alloy tool steels, can generally be distinguished by this method.

Dendritic Structure present in cast steel and persisting in wrought steels may be revealed by the use of Oberhoffer's reagent, which has the following composition:

30	g	ferric chloride ($FeCl_3$)
1	g	cupric chloride ($CuCl_2$)
0.5	g	stannous chloride ($SnCl_2$)
50	ml	muriatic acid (HCl)
500	ml	ethyl alcohol
500	ml	water



Welding Effects in Stainless Steel. Conditions shown are entirely satisfactory. Magnification about 2½ ×. Etched in the "weld etch" containing HCl, $FeCl_3$, HNO_3 and $(NH_4)_2S_2O_8$ in water (see text)

A polished section is etched by immersion for 30 sec to 2 min. Continuing the etching for too long a period deposits an excessive amount of copper, which may obliterate the details of the dendritic structure.

After a prior etch with 10% nitric acid in ethyl alcohol (10% nital), dendritic structure may be revealed by use of another etchant, which contains:

40 g	ferric chloride ($FeCl_3$)
3 g	cupric chloride ($CuCl_2$)
40 ml	muriatic acid (HCl)
500 ml	water

The surface, which may either be smoothly ground through 00 emery paper or have a metallographic polish, is first etched with 10% nital for 10 to 20 sec, washed and dried. It is then immersed in the ferric chloride — cupric chloride reagent (Dickenson's reagent) for 15 to 30 sec. The dendritic pattern that is developed by this etching is revealed by visual examination in incident light.

Sulfur Segregation. In an ingot, forging or hot rolled product the distribution of sulfur may be revealed by sulfur printing. The section to be printed should have a smoothly ground surface or a metallographic polish. Ordinary sensitized photographic silver bromide paper, preferably with a semimatte finish, is soaked in 2% sulfuric acid. The emulsion side of the paper is applied for 1 to 2 min to the prepared surface being investigated. The paper should not be moved after making contact with the specimen. Air bubbles should be rubbed out carefully with a roller or squeegee. The paper should be rinsed with water after removal from the specimen, fixed in a hypo solution, washed thoroughly and dried.

The brown pattern of silver sulfide formed on the paper indicates the relative distribution of sulfur as sulfide inclusions in the steel. The best results are obtained only on first or second prints made from a surface.

Phosphorus Segregation can be revealed by etching reagents that, when properly used, will deposit copper selectively on areas low in phosphorus.

Stead's reagent No. 1 contains:

1 g	cupric chloride ($CuCl_2$)
4 g	magnesium chloride ($MgCl_2$)
2 ml	muriatic acid (HCl)
100 ml	ethyl alcohol

Etching requires immersion of the polished face for 10 to 15 sec. Polished sections of wrought iron and 1213 steel, for example, show a clear delineation of phosphorus segregate areas with a 15-sec etching period.

Stead's reagent No. 2, which contains five times as much cupric chloride, has the following composition:

5 g	cupric chloride ($CuCl_2$)
4 g	magnesium chloride ($MgCl_2$)
1 ml	muriatic acid (HCl)
20 ml	water
100 ml	ethyl alcohol

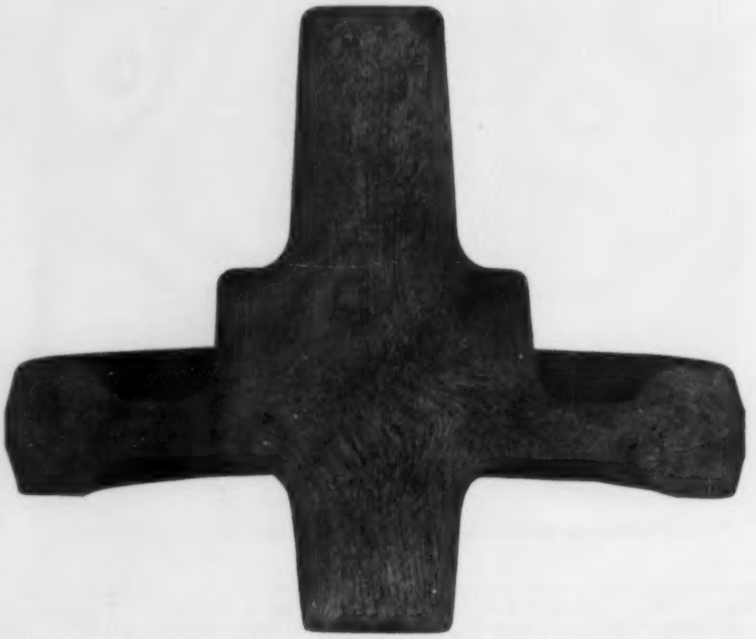
Etching of a polished surface requires immersion. The No. 2 reagent etches more rapidly than No. 1; for example, an etching period of 5 sec will reveal phosphorus segregate areas in wrought iron.

Too long an etching period with these reagents permits copper deposition even in phosphorus-segregated areas, thus obscuring the presence of the segregate. Stead's No. 1 reagent in particular is sensitive to concentration, and excessive evaporation of the ethyl alcohol in this solution results in no deposition of copper during etching for the prescribed period.

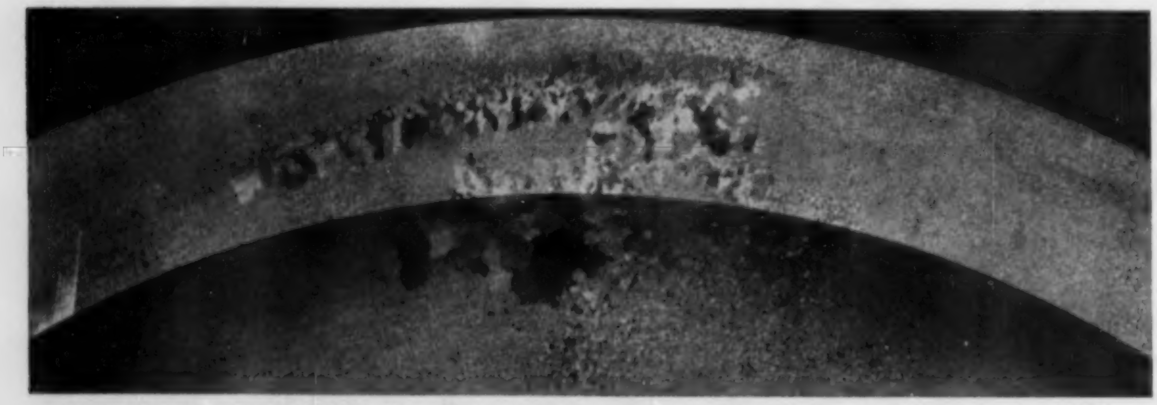
Recrystallization Structures of Weldments and grain flow patterns in stainless steels are revealed by etching at room temperature in Marble's reagent:

4 g	cupric sulfate ($CuSO_4$)
20 ml	muriatic acid (HCl)
20 ml	water

The surface to be etched should be smoothly ground. The specimen must be immersed in the solution for 1 to 2 hr to develop the structure of both the weld metal and grain flow.



Grain Flow Resulting from Forging of Gear Blank. About ½ size. Etched in 50% HCl at 160 to 180 F



Localized Coarse Grain in High-Alloy Steel. Diameter of part approximately 15½ in. Etched in ferric chloride

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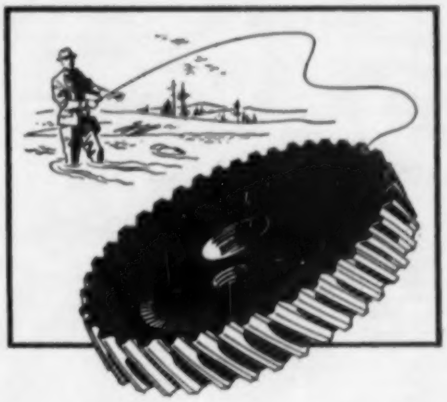
BUSINESS IN MOTION

To our Colleagues in American Business . . .

It is a characteristic of American companies that they constantly seek to improve their products; this is in part responsible for the amazing strides made by industry. Revere is glad to aid in this endeavor through its Technical Advisory Service, and its Research Department, particularly for firms whose need for research is not such as to warrant purchasing costly laboratory equipment. A recent problem presented to us came from a maker of fishing reels. He had been cutting gears out of free-cutting brass, in order to achieve the machining economies such material offers.



This brass is widely and successfully used in gears for clocks, meters, and similar instruments. However, experience proved that a fishing reel, which is operated at various speeds and loads, presents a quite different service. Revere was asked to suggest a metal that would be more suitable in this application.

The Technical Advisory Service at once reported that either naval brass or aluminum silicon bronze would last longer. However, in order to determine the relative merits of the two, the Revere Research Department was asked to make tests. Gears of both metals were installed in reels, and a motor-driven machine was rigged to provide an accelerated wear test. Each gear was run at 430 r.p.m. and at 100 r.p.m., at zero tension on the line, and at 1, 2, 3, and 4 pounds tension. After each run the gears were removed, cleaned, examined, measured and photographed. The reels were then reassembled, lubricated, and the next run started.

The results were impressive. After the gears had gone through 186,727 revolutions it was felt unnecessary to proceed further. Both reels were still fully usable. The naval brass was somewhat more worn than the aluminum silicon bronze, however, it certainly was evident that naval brass would be satisfactory. The reel maker was determined to offer the best he knew how to make, and selected the more expensive aluminum silicon bronze. He knows conclusively now that his reels will give long service, enduring satisfaction, and will protect his reputation and help his business grow.

If you have questions as to the best material or materials for your product, no matter what it is, and do not have a modern research laboratory, why not ask your suppliers for help? Some may have an immediate answer; some may wish to test alternatives. You will benefit either way, and make faster and surer progress in your search for improvement.

REVERE COPPER AND BRASS INCORPORATED
Founded by Paul Revere in 1801
Executive Offices: 230 Park Avenue, New York 17, N. Y.

ELECTROMET

TRADE-MARK

ALLOYS FOR THE STEEL, IRON, AND NON-FERROUS INDUSTRIES

BORON ALLOYS

Ferroboron **Min. 10.00% Boron Grade**	Aluminum ...max. 0.50% Carbon .....max. 1.50%	Increases hardenability of steel; also, for additions to malleable iron and aluminum alloys.
Min. 17.50% Boron Grade	Aluminum ...max. 0.50% Carbon .....max. 0.50%	
Manganese-Boron	Boron .....min. 17.50% Manganese ..approx. 75% Carbon ....max. 3% Iron ....max. 5%	Used to cleanse and deoxidize non-ferrous alloys.

CALCIUM ALLOYS

Calcium-Silicon	Calcium ......30 to 33% Silicon ....60 to 65% Iron ....1.50 to 3%	Deoxidizer for high-quality steel. Also used in high-tensile gray irons.
Calcium-Manganese-Silicon	Calcium ......16 to 20% Manganese ...14 to 18% Silicon ......53 to 59%	A complex deoxidizer used widely in production of steel castings.
Calcium Metal **Regular Grade**	Calcium ....98% Balance largely Calcium Chloride	Deoxidizer and degasifier for steel and non-ferrous metals.
Distilled Grade	Calcium..approx. 99.50% Balance largely Magnesium	For special applications requiring calcium of very high purity.

CHROMIUM ALLOYS

"Simplex" Low-Carbon Ferrochrome No. 1	Chromium ....63 to 66% Silicon ....5 to 7% Carbon ....max. 0.010% or 0.025%	Suitable for all grades of steel containing chromium, and especially designed for stainless and high-alloy steels where substantial quantities of chromium are required. The silicon in the No. 1 alloy provides means of reducing metal oxides back from the slag and also increases the rate of solubility of the ferrochrome, thus providing a saving in furnace time. For those applications where high silicon is undesirable, "Simplex" No. 2 has been designed to provide an alloy which gives the desired characteristics of very close carbon control together with high chromium recoveries.
2% Nitrogen-Bearing Grade	Chromium ....62 to 65% Silicon ....5 to 7% Nitrogen ......2 to 2.5% Carbon ....max. 0.025%	
5% Nitrogen-Bearing Grade	Chromium ....60 to 63% Silicon ....5 to 7% Nitrogen ......5 to 6% Carbon ....max. 0.025%	
"Simplex" Low-Carbon Ferrochrome No. 2	Chromium ....63 to 66% Silicon .....max. 1.50% Carbon .....max. 0.03%	
2% Nitrogen-Bearing Grade	Chromium ....62 to 65% Silicon .....max. 1.50% Nitrogen .....2 to 2.5% Carbon .....max. 0.03%	
5% Nitrogen-Bearing Grade	Chromium ....60 to 63% Silicon .....max. 1.50% Nitrogen ......5 to 6% Carbon .....max. 0.03%	
Low-Carbon Ferrochrome (Other Grades)	Chromium ....67 to 71% Silicon ...0.30 to 1.00% Carbon (10 Grades) max. 0.02 to max. 2.00%	Production of stainless steels and high-temperature alloys requiring low carbon content.
High-Carbon Ferrochrome **2.25 to 3.00% Carbon Grade**	Chromium ....66 to 70% Silicon ....max. 2% Sulphur .....max. 0.03%	Suitable for the production of all grades of alloy steel, including the high alloys, such as stainless steel.
Max. 4.50, 5.00, or 6.00% Carbon Grade	Chromium ....67 to 70% Silicon ....1 to 2%	
Max. 7.00% Carbon Grade	Chromium ....66 to 69% Silicon ....1 to 3%	
Min. 7.00% Carbon Grade	Chromium ....65 to 68% Silicon ....1 to 3%	
57 to 64% Chromium Grade	Carbon ......3.5 to 5% Silicon ....2 to 4.5%	
Nitrogen-Bearing Low-Carbon Ferrochrome	Chromium ....65 to 70% Silicon ...0.30 to 1.00% Carbon .....max. 0.10% Nitrogen ..0.75 to 2.00%	For additions of nitrogen to improve properties of high-chromium steels.
"SM" Ferrochrome	Chromium ....60 to 65% Silicon ....4 to 6% Carbon ....4 to 6% Manganese ....4 to 6%	A high-solubility chromium addition for steel or iron in either furnace or ladle.

CHROMIUM ALLOYS cont.

Exothermic Ferrochrome 5	Chromium ..approx. 50% Carbon ....approx. 2.5%	These improved exothermic ladle alloys have high solubility, low carbon pickup, and high ignition temperature.
Exothermic Ferrochrome 8	Chromium ..approx. 48% Carbon .....approx. 4%	
Exothermic Silicon-Chrome	Chromium ..approx. 46% Silicon .....approx. 23% Carbon .....max. 1.00%	
Foundry Ferrochrome **High-Carbon Grade**	Chromium ....62 to 66% Silicon ....7 to 10% Carbon ....5 to 7%	A high-solubility ferrochrome, developed especially for ladle additions of chromium to cast iron.
Low-Carbon Grade	Chromium ....50 to 54% Silicon ....28 to 32% Carbon .....max. 1.25%	
Chromium Metal **High-Carbon Grade**	Chromium ....87 to 90% Carbon ....9 to 11% Iron ....max. 1.25%	For production of a wide variety of chromium-bearing alloys, including electrical resistance alloys and high-temperature alloys.
Electrolytic Grades **Laboratory Grade**	Chromium ..min. 99.20% Iron ....max. 0.03%	
Commercial Grade	Chromium ..min. 99.00% Iron ....max. 0.30%	
"EM" Ferrochrome-Silicon	Chromium ....39 to 41% Silicon ....42 to 46% Carbon ......max. 0.05%	Used essentially in the production of stainless steel.
"EM" Ferrosilicon-Chrome	Chromium ....50 to 54% Silicon ....28 to 32% Carbon ......max. 1.25%	For adding chromium and silicon to steels containing up to 1 or 2 per cent chromium.
"EM" Chromium Briquets **(Hexagonal Shape)**	Chromium ....2 lb. Total Weight .....3⅜ lb.	For adding chromium to cast iron in the cupola.

COLUMBIUM ALLOYS

Ferrocolumbium	Columbium ...50 to 60% Silicon ....max. 8% Carbon .....max. 0.40%	Stabilizer in austenitic chromium-nickel stainless steels. Also constituent of high-temperature alloys.
Ferrotantalum-Columbium	Columbium ..approx. 40% Tantalum ...approx. 20% Cb + Ta ....min. 60% Carbon .....max. 0.30% Iron ......approx. 25%	Used to supplement ferrocolumbium in chromium-nickel stainless steels and high-temperature alloys.

MANGANESE ALLOYS

Standard Ferromanganese **Regular Grade**	Manganese ...74 to 76% Carbon ......approx. 7% Silicon ....max. 1%	Most common means of adding manganese to steel for both alloying and deoxidizing purposes. Also for counteracting sulphur in steel and cast iron.
Low-Phosphorus Grade	Manganese ...78 to 80% Carbon ....max. 7% Silicon ....max. 2% Phosphorus ..max. 0.10%	
Low-Carbon Ferromanganese **Low-Phosphorus Grade**	Manganese ....min. 90% Carbon .....max. 0.07% Phosphorus ..max. 0.06%	Used for making additions of manganese to steels of low-carbon specification, particularly stainless steels.
Regular Grades	Manganese ...85 to 90% Carbon ..max. 0.07, 0.10, 0.15, 0.30 or 0.50%	
Regular Grade (High-Silicon)	Manganese ...80 to 85% Carbon .....max. 0.75% Silicon ....5 to 7%	
"Mansiley" Alloy	Manganese ...60 to 63% Silicon ......28 to 31% Carbon .....max. 0.07% Phosphorus ..max. 0.05%	Used essentially in the production of stainless steels.
Silicomanganese **Max. 1.50% Carbon Grade**	Manganese ...65 to 68% Silicon ....18 to 20%	A versatile alloy useful as a furnace block and deoxidizer, and also for an alloy addition to steel in the ladle or furnace.
Max. 2.00% Carbon Grade	Manganese ...65 to 68% Silicon ....15 to 17.50%	
Max. 3.00% Carbon Grade	Manganese ...65 to 68% Silicon ....12 to 14.50%	

All of the alloys and metals listed are produced in the usual lump, crushed, or ground sizes, except where other special forms are indicated.

MANGANESE ALLOYS cont.

Medium-Carbon Ferromanganese	Manganese ...80 to 85% Carbon ....1.25 to 1.50% Silicon.max. 1.00 or 1.50%	An intermediate carbon ferromanganese alloy for addition to steel.
Low-Iron Ferromanganese	Manganese ...85 to 90% Carbon ...approx. 7.00% Silicon ....max. 3% Iron ....max. 2%	For high manganese additions to certain non-ferrous alloys, particularly aluminum.
Manganese Metal Electrolytic Grade	Manganese .min. 99.90%	Used wherever manganese of high purity is required in the production of stainless steel and non-ferrous alloys.
Nitrogen-Bearing Grade	Manganese ..approx. 93% Nitrogen ....approx. 6%	
"EM" Silicomanganese Briquets (Square Shape)	Manganese ....2 lb. Silicon ....½ lb. Total Weight .....3½ lb.	For adding manganese (with silicon) to cast iron in the cupola.
"EM" Ferromanganese Briquets (Oblong Shape)	Manganese ....2 lb. Total Weight ....3 lb.	For adding manganese (without silicon) to cast iron in the cupola.

SILICON ALLOYS

50% Ferrosilicon Regular Grade	Silicon ....47 to 51%	Deoxidizer for most grades of killed or semi-killed steel. The blocking grade is specially sized for maximum efficiency.
Blocking Grade	Silicon ......47 to 51%	
Boron-Bearing Grade	Silicon ......47 to 51% Boron ....0.04 to 0.05% Or higher if desired	
Low-Aluminum Grade	Silicon ......47 to 51% Aluminum ...max. 0.40% or 0.10%	
65% Ferrosilicon Regular Grade	Silicon ....65 to 70%	For furnace or ladle addition to steels.
Low-Impurity Grade	Silicon ..61.50 to 66.50% Aluminum ...max. 0.50% Total Impurities max. 1.00%	Commonly used for production of electrical sheet steel.
75% Ferrosilicon Regular Grade	Silicon ....73 to 78%	Deoxidizer and alloy for production of high-silicon spring and electrical sheet steel. Graphitizing inoculant for cast iron.
Low-Aluminum Grade	Silicon ....73 to 78% Aluminum ...max. 0.50%	
85% Ferrosilicon Regular Grade	Silicon ....83 to 88%	Enables melter to add higher percentages of silicon without chilling metal in ladle. Graphitizing inoculant for cast iron.
Calcium-Bearing Grade	Silicon ......83 to 88% Calcium ....min. 0.50%	
Low-Aluminum Grade	Silicon ....83 to 88% Aluminum ...max. 0.50%	
90% Ferrosilicon Regular Grade	Silicon ....92 to 95%	Permits large additions of silicon without harmful chilling effect.
Low-Aluminum Grade	Silicon ....92 to 95% Aluminum ...max. 0.50%	
Silicon Metal Regular Grade	Silicon min. 98 or 96.50% Iron..max. 0.75 or 1.50% Calcium ....max. 0.07%	Additions of silicon to non-ferrous metals, particularly aluminum and copper.
Purified Grade	Silicon ..99.70 to 99.90% Iron ......005 to .015%	For applications in non-ferrous industry requiring silicon of high purity.
Low-Calcium Grade	Silicon ....min. 98% Iron ....max. 0.75% Calcium ....max. 0.03%	For high-silicon aluminum alloys where calcium is detrimental.
Low-Aluminum Grade	Silicon .....min. 98.50% Iron ....max. 0.75% Aluminum ...max. 0.10% Calcium ....max. 0.03%	For the production of silicon-copper alloys where aluminum is detrimental.
"EM" Silicon Briquets Large Size (Cylindrical or Brick-Shape)	Silicon ....2 lb. Total Weight ......5 lb.	For adding silicon to cast iron in the cupola.
Small Size (Cylindrical Shape)	Silicon ....1 lb. Total Weight .....2½ lb.	

SILICON ALLOYS cont.

"SMZ" Alloy	Silicon ....60 to 65% Manganese ....5 to 7% Zirconium .....5 to 7%	Particularly strong graphitizing inoculant used in cast iron.
Magnesium-Ferrosilicon Regular Grade	Silicon ....43 to 47% Magnesium ..7.5 to 9.5%	For addition to cast iron and steel to obtain special properties.
Cerium-Bearing Grade	Cerium ...approx. 0.50%	

TITANIUM ALLOYS

Ferrotitanium	Titanium ..27 to 32%, 50 to 55%, or approx. 70% Carbon .....max. 0.10%	For stabilized stainless steels and high-temperature metals.
Silicon-Titanium	Titanium .....40 to 50% Silicon ....45 to 50% Iron ....max. 3%	For additions of titanium to steel, cast iron, or nonferrous alloys.
Manganese-Nickel-Titanium	Titanium ...approx. 48% Nickel .....approx. 31% Manganese .approx. 6%	For adding nickel and titanium to high-temperature alloys.

TUNGSTEN ALLOYS

Ferrotungsten	Conforming to A.S.T.M. Spec. A 144-50	Production of tool and die steels; also high-temperature alloys.
Tungsten Metal Powder Melting Grade	Tungsten ...min. 98.80% Total Carbon..max. 0.25%	Production of tungsten steels and cast tungsten carbide.
Calcium Tungstate	Tungstic Oxide.68 to 72%	For making tungsten chemicals and other tungsten products.
Calcium Tungstate Nuggets	Tungstic Oxide.68 to 72%	For producing tool steels and high-temperature alloys.
Ammonium Paratungstate	Tungstic Oxide.min. 88.7%	Intermediate for tungsten products.

VANADIUM ALLOYS

Aluminum-Vanadium	Vanadium ....80 to 85% Aluminum ....13 to 16% Iron ....max. 1% Silicon ....max. 1% Oxygen .....max. 0.25%	For adding aluminum and vanadium to titanium metal and alloys.
Ferrovanadium	Vanadium ....50 to 55% or 70 to 75% Carbon ..max. 0.20, 0.50, or 3.00% Silicon ..max. 1.50, 2.00, or 8%; and approx. 10%	Production of tool and engineering steels, high-strength structural steels, non-aging rimming steels, and wear-resistant irons.
Vanadium Oxide Fused	V_2O_5 ....86 to 89% Na_2O ....approx. 10% CaO ....approx. 2%	For addition of vanadium to steel and for manufacturing catalysts.
Sodium Polyvanadate (Red Cake)	V_2O_5 ....approx. 85% Na_2O ....approx. 9%	For manufacture of vanadium compounds, including vanadium catalysts.
High-Purity	V_2O_5 ....approx. 99.50%	
Ammonium Metavanadate	NH_4VO_3 ....min. 99%	

ZIRCONIUM ALLOYS

12 to 15% Zirconium Alloy	Zirconium ....12 to 15% Silicon ....39 to 43% Carbon .....max. 0.20%	A powerful deoxidizer. Also increases depth of hardening of steel.
35 to 40% Zirconium Alloy	Zirconium ....35 to 40% Silicon ......47 to 52% Carbon .....max. 0.50%	Steel deoxidizer when higher concentration of zirconium is desired.
"EM" Zirconium Briquets (Cylindrical Shape, Red Color)	Zirconium ....0.55 lb. Silicon ....1.90 lb. Total Weight ....5 lb.	For adding zirconium and silicon to cast iron in the cupola.

"Electromet," "EM," "Mansiloy," "Simplex," "SM," and "SMZ," are trade-marks of Union Carbide and Carbon Corporation.

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Metallographic Polishing With Diamond Abrasives*

THE ADVANTAGES of a system of mechanical polishing, based on the use of diamond abrasives, for the routine preparation of both ferrous and nonferrous materials, are described. The stages of the basic system are as follows:

1. *Abrasive Papers* – Silicon carbide waterproof papers; hand operated with flowing water lubricant: (*a*) 220-mesh or (*b*) 400-mesh grade.
2. *Abrasive Lap* – Cast alumina-wax lap; hand operated, dry.
3. *Rough Polishing* – Diamond paste abrasive on napped cloth; kerosene lubricant, hand or, preferably, machine operated: (*a*) coarse stage, 4 to 8-μ grade (optional); (*b*) fine stage, 0 to 1-μ grade.
4. *Finish Polishing* – Calcined magnesium oxide paste on Selvyt cloth; polishing may be either by hand or machine.

The treatment of various specimens is claimed to differ only at finish polishing (Stage 4). In this stage specimens of the softer metals are handled by the "skid" polishing technique, those of the harder metals are finished by the common technique of using a thin slurry of magnesia in water. As a third embellishment, some of the extremely soft metals are etch-polished by the skid process in which a quantity of the etchant is added to the magnesia paste.

The really unique feature of this system lies in the employment of the cast alumina-wax lap between grinding on the abrasive papers and the first polishing with diamond paste. Unfortunately, the preparation and use of this lap is not described in this paper. The original work by Samuels in the *Journal* of the Institute of Metals (Vol. 81, 1952-53, p. 471) must be consulted for these details. The lap makes it possible to go directly to fine polishing in one step.

(Continued on p. A-86)

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*Digest of "Practical Applications of a System of Metallographic Polishing Using Diamond Abrasives", by L. E. Samuels and M. Hatherly, *Metallurgia*, Vol. 50, December 1954, p. 303-308.

VANCORAM PRODUCTS

ALSIFER and ALUMINUM ALLOYS

PRODUCT	TYPICAL COMPOSITION
Alsifer	Aluminum ....20% Silicon ....40% Iron 40%
Aluminum Alloys Deoxidizing Grades	Aluminum ...85 to 99%
Silicon Aluminum	Silicon ....5 to 20% Aluminum ....Bal.
Titanium Aluminum	Titanium....2½ and 5% Aluminum ....Bal.
Vanadium Aluminum	Vanadium ..2½, 5, 10% Aluminum ....Bal.

BORON ALLOYS

PRODUCT	TYPICAL COMPOSITION
Ferroboron	Boron ....14/18% Carbon ....0.20% Silicon .....max. 3.00% Aluminum ..max. 3.00%
Vanadium Grainal No. 1	Vanadium ......25.00% Aluminum ......10.00% Titanium ....15.00% Boron 0.20%
Grainal No. 79	Aluminum ......13.00% Titanium ......20.00% Zirconium ....4.00% Manganese ......8.00% Boron ....0.50% Silicon .....max. 5.00%

CHROMIUM ALLOYS

PRODUCT	TYPICAL COMPOSITION
Ferrochromium Briquettes	Hexagonal in shape. Weigh approx. 3⅜ lb. and contain 2 lb. of chromium.
High Carbon Grade	Chromium .....66/70% Carbon 4/6%
Iron Foundry Grade	Chromium .....62/66% Carbon ....4/6% Silicon 6/9%
Low Carbon Grades	Chromium .....67/72% Carbon ..... .06%, .10% .15%, .20%, .50%, 1.00% and 2.00% max.
Exlo® Max. .025 Carbon Grade	Chromium .....67/72% Carbon ....max. 0.025% Silicon .....max. 1.00%
Max. .06 Carbon Grade	Chromium .....67/72% Carbon .....max. 0.06% Silicon .....max. 1.00%
Ferrochrome-Silicon Low Carbon Ferrochrome-Silicon	Chromium .....39/42% Silicon ....40/42% Carbon .....max. 0.05%
Experimental Ferrochrome-Silicon Alloy	Chromium .....48/52% Silicon ....25/30% Carbon .....max. 1.50%

MANGANESE ALLOYS

PRODUCT	TYPICAL COMPOSITION
Ferromanganese Briquettes	Oblong in shape. Weigh approx. 3 lb. and contain 2 lb. of manganese.
Silicomanganese Max. 1.50% Carbon Grade	Manganese ....65/68% Silicon 18/20%
Max. 2.00% Carbon Grade	Manganese ....65/68% Silicon 15/17.5%
Max. 3.00% Carbon Grade	Manganese ....65/68% Silicon 12/14.5%

SILICON ALLOYS

PRODUCT	TYPICAL COMPOSITION
Ferrosilicon Briquettes	Two sizes, both cylindrical. The smaller contains 1 lb. of silicon; the larger, 2 lb. of silicon.
25% Grade	Silicon 22/26%
50% Grade	Silicon 47/52%
Silblok* 25 & 50	Same as above
65% Grade	Silicon 65/69%
75% Grade	Silicon 74/79%
80/85% Grade	Silicon 80/84.9%
85/90% Grade	Silicon 85/89.9%
90/95% Grade	Silicon 90/95%

Low aluminum grades of ferrosilicon also available.

*Trade-mark

SILICON METAL

PRODUCT	TYPICAL COMPOSITION
Max. 1.00% Iron Grade	Silicon ....min. 97% Iron ....max. 1%
Max. 2.00% Iron Grade	Silicon ......min. 96% Iron ....max. 2%
Low Calcium Grade	Silicon ......min. 97% Iron ....max. 1% Calcium .....max. 10%

SPECIAL FOUNDRY ALLOYS

PRODUCT	TYPICAL COMPOSITION
Graphidox No. 4	Silicon ....48/52% Titanium ....9/11% Calcium 5/7%
Noduloy Alloys (Various Types)	Magnesium ...5/16.5% Silicon ....37/67% Copper ....0/18% Iron ....Bal.
V-5 Foundry Alloy	Chromium .....38/42% Silicon ....17/19% Manganese 8/11%

TITANIUM ALLOYS

PRODUCT	TYPICAL COMPOSITION
Ferrotitanium High Carbon Grade	Titanium ......15/18% Carbon 6/8%
Medium Carbon Grade	Titanium ......17/21% Carbon 3/4.50%
Low Carbon Grades 30% Titanium	Titanium ......27/32% Carbon ....max. 0.10% Silicon .....max. 4.00% Aluminum ..max. 5.00%
40% Titanium	Titanium ......38/43% Carbon ....max. 0.10% Silicon .....max. 4.00% Aluminum ..max. 8.00%
27/32% Titanium Special (Various Types)	Titanium ......27/32% Carbon ....max. 0.10% Silicon .....max. 2.50% & 5.00% Aluminum ..max. 1.50 to 2.50%

VANADIUM ALLOYS

PRODUCT	TYPICAL COMPOSITION
Ferrovanadium Iron Foundry Grade	Vanadium .....38/42% Silicon ....7/11% Carbon ......about 1%
Grade A (Open Hearth)	Vanadium .....50/55% Silicon .....max. 7.50% Carbon .....max. 2.00%
Grade B (Crucible)	Vanadium .....50/55% 70/80% Silicon .....max. 2.25% Carbon .....max. 0.50%
Grade C (Primos)	Vanadium .....50/55% 70/80% Silicon .....max. 1.25% Carbon .....max. 0.20%

VANADIUM PRODUCTS

PRODUCT	TYPICAL COMPOSITION
Vanadium Metal 90% Grade	Vanadium ......91.45% Aluminum ......1.00% Silicon ....0.90% Carbon 0.10%
99.7% Grade	Vanadium 99.7%
Vanadium Pentoxide Technical Grade— Fused Form	V_2O_5 ....88/92%
Air-Dried Form	V_2O_5 ....83/86%
Ammonium Meta Vandate Technical Grade	NH_4VO_3 ......min. 99%

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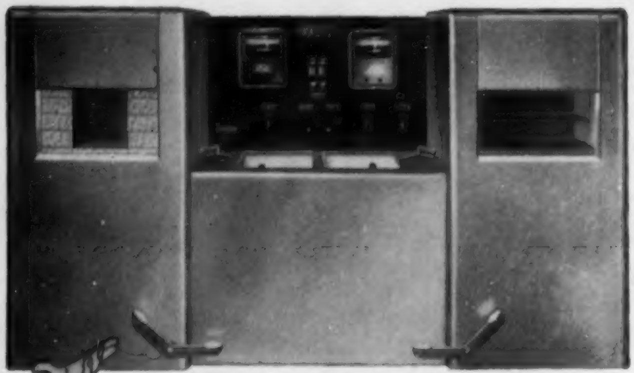

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Polishing . . . .

A substantial lessening of the time required for specimen preparation as well as almost complete freedom from flowed metal layers, is attributed to the use of the diamond abrasives. There is also a marked improvement in specimen flatness and inclusion retention.

Ferrous Materials – The majority of ferrous specimens are in a satisfactory condition for visual examination at the end of the diamond abrasive stages. Specimens to be micrographed should be finished for a short time by the magnesia slurry method. With austenitic materials or lamellar pearlitic specimens where disturbed metal persists, it is suggested that the repolishing be carried back as far as the 4 to 8-μ diamond abrasive. The authors claim that if the technique is correctly carried out no artifacts should appear after the first etching.

Exceptionally good retention of nonmetallic inclusions is obtained consistently by the standard routine procedure. However, coarse flake or nodular graphite constituents are pulled out by the nap of the cloth. The author mentions that remedial measures for this will be discussed in a future publication.

For critical preservation of edges, the author suggests a napless cloth such as heavy cotton drill for the preparation of the diamond polishing pads. The edges of composite specimens, such as electroplated tin or zinc, should be protected by a plate of flash copper over which iron is plated to form a guard for the edges.

Aluminum and Aluminum Alloys – The majority of aluminum alloys can be satisfactorily finished by the conventional magnesia slurry method; the skid polishing method of finishing is recommended for high-purity aluminum. As a precaution against electrolytic attack on aluminum, it is recommended that either an insulating disk be used under the cloth or an aluminum disk be employed.

Magnesium and Copper Alloys – The common cast magnesium alloys are adequately finished by using the magnesia slurry methods. In this

(Continued on p. A-88)

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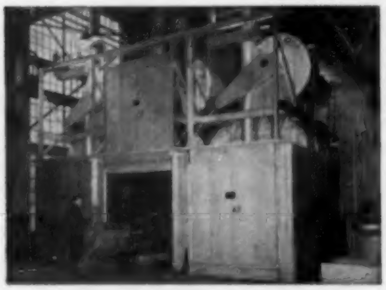

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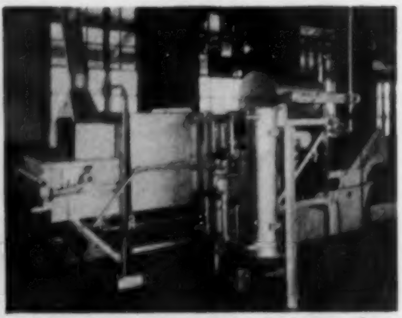

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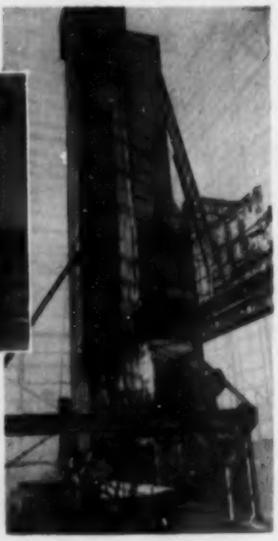
Rockwell continuous belt conveyor, muffle type, gas-fired furnace with long cooling section for bright annealing copper products in controlled atmosphere.



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Polishing . . . .

case distilled water is used in making the slurry. High-purity magnesium must be finished by the skid method. Some difficulty is experienced with water attack, particularly around the inclusions.

The majority of copper alloys are finished by the skid method. It is advantageous to increase the rate of finish by the addition of 0.1 to 0.3% ammonium persulphate to the magnesia paste.

Reviewer's Comments – The authors show thirteen superb examples of metallography. They attribute a large measure of this quality to the use of diamond abrasives. Improvements in both the preliminary grinding and finish polishing stages also contribute to the success of the system. The cast abrasive-wax lap is also a considerable improvement over fine abrasive papers in the production of a flat surface with well-preserved edges and good retention of nonmetallic inclusions.

It should be stated at the outset that metallography is an art rather than a science. Every experienced metallographer has his own techniques for the preparation of specimens. The success of any technique lies in the skill with which it is applied.

The writer stopped using wax laps several years ago when simpler methods became known. When only a few specimens are being prepared, the maintenance of cast wax laps is quite simple but when the specimens number into the hundreds, laps become difficult to maintain in usable condition.

A further thought is relative to the use of magnesia for the final polish. The authors state that it is not necessary to use distilled water with this abrasive except for pure magnesium. Could it be that the water in Australia does not contain dissolved carbonate? In the writer's estimation, there are many better abrasives available for finishing the majority of specimens. We use magnesia only on very difficult materials and then always by the "skid" method. Alumina, sapphire dust, and chromium oxide are satisfactory for work at highest magnifications with

(Continued on p. A-90)

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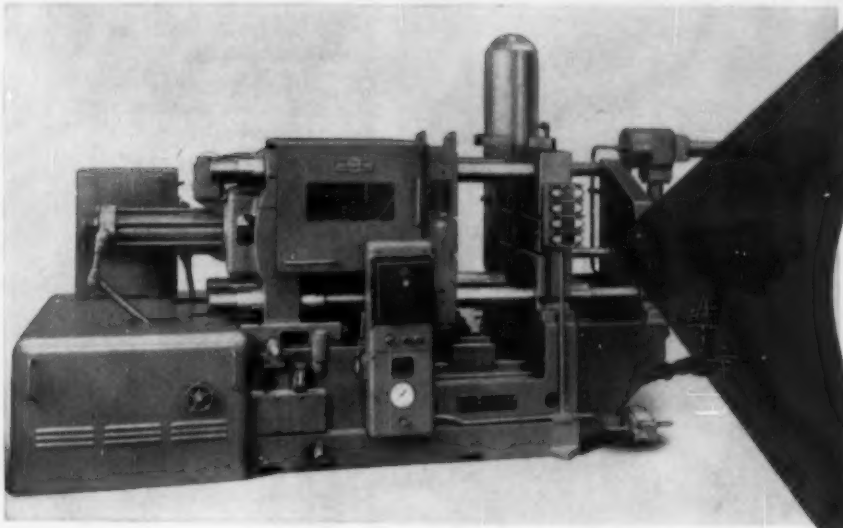

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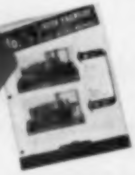

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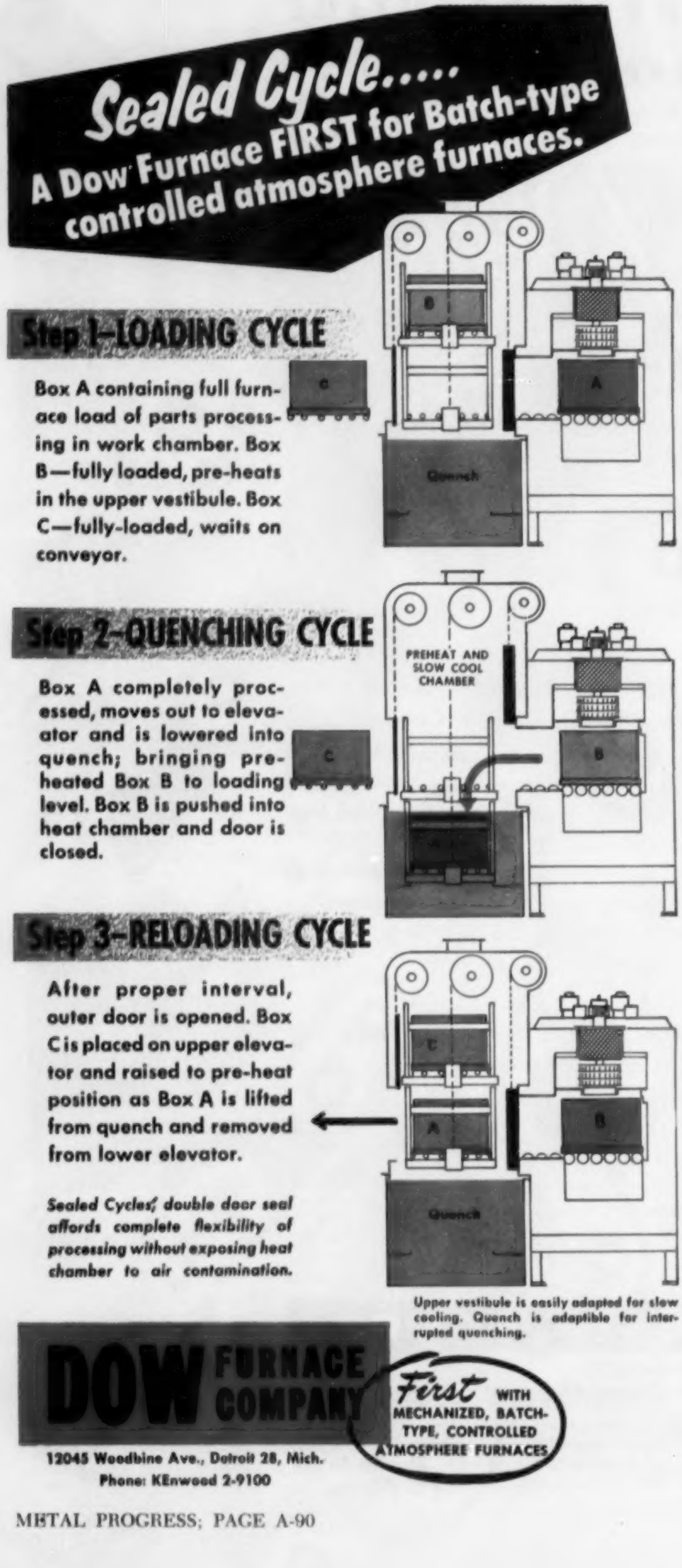

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Polishing . . . .

most specimens. None of these form carbonates and they are much faster and simpler to use.

The general technique employed by the reviewer has for some time been as follows:

1. *Grinding:* (*a*) Rough grinding: No. 3 emery paper on a rotary disk grinder. (*b*) No. 1, 0, 2/0 and 3/0 metallographic emery polishing paper on a glass plate with paraffin-kerosene mixture as lubricant for the 3/0 step, earlier if abrasive has a tendency to embed in the specimen. (*c*) Buehler No. 1434 Microcut paper on glass plate. This paper is better after some use.

2. *Polishing:* (*a*) 4 to 8-μ diamond (Diamet Hyprez, Buehler No. 1548), on red felt. (*b*) 0 to 2-μ diamond (Diamet Hyprez, Buehler No. 1546), on red felt as above. (*c*) 0 to ½-μ diamond (Diamet Hyprez, Buehler No. 1544), on microcloth. As a lubricant, Diamet Hyprez fluid (Buehler No. 1542) is used with all grades of diamond. This is applied very sparingly with an atomizer. Carbon tetrachloride is dangerously toxic and is used only in a good hood for washing specimens between wheels. There is considerable variation in the quality and reliability of the diamond polishing compounds. No trouble has ever been experienced when Diamet Hyprez has been used.

3. *Finishing:* It has never been found necessary to finish any material of the hardness of soft steel or above beyond the diamond wheels, even for work at highest magnifications. Softer materials are finished on a Miracloth (Buehler No. 1595) wheel using Metpolish No. 3, Buehler No. 1564. Extremely soft materials are finished on silk velvet using Shamva, always by the skid polishing technique.

The prevention of the formation of disturbed metal layers (artifacts) is a matter of making sure that every stage in the polishing process is an efficient cutting one. Flowed metal is produced by rubbing (buffing) and not cutting.

While diamond abrasives are expensive to buy and use, if the number of specimens per hour and the

(*Continued on p. A-92*)

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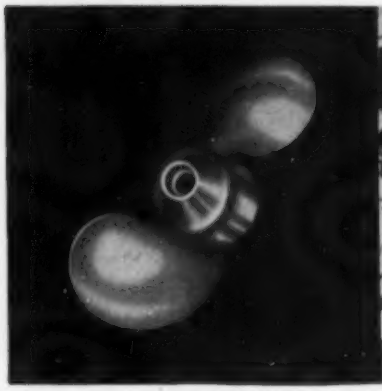

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Polishing . . . .

cost of labor are considered, the economics of the production of polished specimens and the quality of the finished work are greatly in favor of diamond abrasives.

If the specimens are very soft materials, the diamond polishing (Step 2) is best omitted in its entirety and an intermediate polishing step using sapphire dust (Micropolish, Buehler No. 1549) on Miracloth is used for a coarse polishing step.

ROY L. ANDERSON

Production and Heat Treatment of Light-Alloy Drop Forgings*

TIGHTER dimensional tolerances, along with demands for higher strength and careful control of metallurgical properties, have introduced new procedures in the production of aluminum and magnesium alloy drop forgings for the aircraft industry. They include such factors as die design, forging design, choice of forging stock, heat treatment, pickling and inspection. Quality control extends to tensile tests on specimens taken from forged bars at various angles to the grain direction, hardness tests on finished forgings, macro and micro-examination.

Drop forgings made in closed dies require impressions to be sunk into both die faces. The parting line is determined by the general symmetry of the forging. Where several alternatives are present, the choice is governed by such metallurgical or mechanical factors as grain flow and strength required in service.

Die faces normally are flat, but some forgings can be shaped only by "stepping" or inclining the faces at an angle. Dies generally are of Ni-Cr-Mo steel and are machined in

(Continued on p. A-94)

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*Digest of "The Production of Light-Alloy Drop-Forgings, Their Heat Treatment, Inspection, and Testing", by W. T. Edmunds and R. C. Lloyd, *Journal of the Institute of Metals*, Vol. 83, February 1955, p. 247-261.

FOR DEGREASING, DESCALING AND ELECTROPLATING

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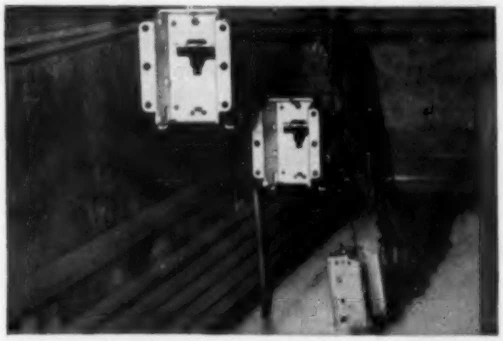

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FOR VAPOR DEGREASING: You get bright, thorough cleaning for any class work . . . in any vapor degreaser with TRICLENE® D trichlorethylene. An exclusive Du Pont formulation gives it rugged resistance to *all* the major causes of solvent deterioration . . . yet TRICLENE D cleans safely even the most delicate metal surfaces. This means a higher standard of vapor degreasing and reduced maintenance cost . . . at no extra cost to you!

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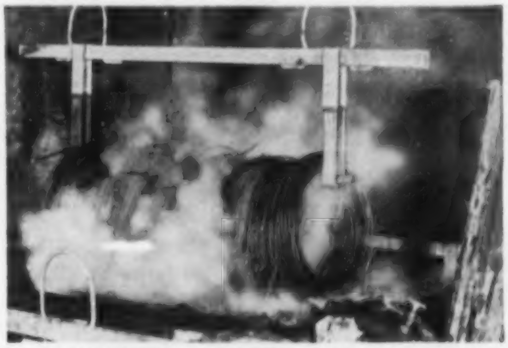
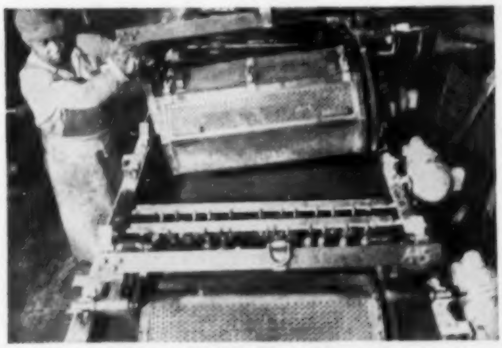


AFTER SODIUM HYDRIDE TREATMENT, reduced scale on carbon steel wire is blasted off with a water quench.



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For Copper Plating: COPPRALYTE® plating salts.

For Copper and Silver Plating: Sodium Cyanide and Potassium Cyanide.

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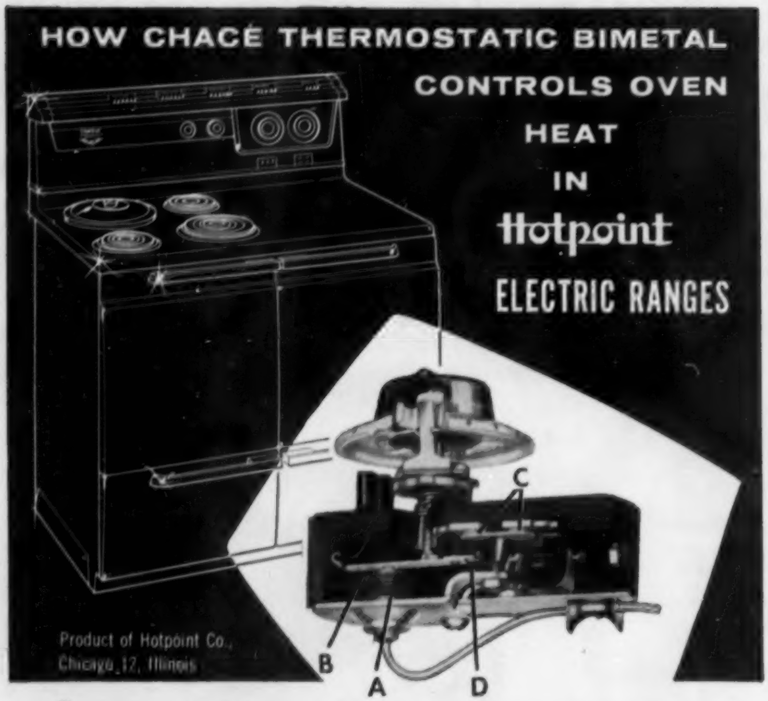

During the last fifty years, the Hotpoint Company has pioneered in the development of the electric range to its present highly refined state. Naturally, dependable regulation of oven temperatures is essential to efficient operation. Therefore, the Hotpoint range depends upon Chace Thermostatic Bimetal as an integral part of the temperature controlling thermostat.

The Hotpoint thermostat functions to control oven heat by two means: an oven-mounted sensing bulb reacts to a preset temperature by the expansion of contained fluids which impart a force on the expansible and contractible bellows assembly (A), and on the operating blade (B), to break the circuit of the double pole contacts (C), with a snap-action.

Since much of the fluid contained within the bellows assembly is *exterior* to the oven and subject to the expansion and contraction effects of extraneous temperatures, Chace Thermostatic Bimetal (D) is employed in a section of the operating blade to function as an automatic compensator for eliminating the effects of undesired temperature sensing. Its flexing adds to or subtracts from the forces of curvature of the operating blade depending upon whether the temperature is below or above the design base—average room temperature.

Prolonged oven operation will cause a temperature build-up in the range backsplasher (as high as 200° F.) so that the range, if not provided with a compensating Chace Thermostatic Bimetal element, would supply temperatures some 120° F. lower than desired.

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Drop Forgings . . . .

the hardened and tempered condition to avoid distortion.

Die life is related to the design of the particular forging. Some dies are good for up to 2000 pieces; however, where the design involves sharp radii, uneven sections, deep lugs or bosses, runs will be much shorter because of erosion and cracking. An important factor is the lubricant used on dies. Oil impregnated with graphite, and petroleum jelly with graphite are common combinations.

Pre-Formed Blanks Favored

Forging of aluminum alloys is done at 680 to 900° F., depending upon the alloy involved. Actually, there is comparatively little movement of metal in the die impression. For normal forgings, the blank, usually pre-formed by hand or free-forging methods, is approximately the length and width of the die impression. Displacement of metal is confined to bosses and lugs, with excess material being forced into the flash. A recess or "gutter" is sunk into the die a short distance from the impression to provide an outlet for flash later to be removed by band saw or press trimming dies.

Hammer sizes must be considered carefully in relation to the weight of the blank or pre-form. Usual range is 5 to 20 tons gross weight. Forgings with small radii may require a considerable number of blows and reheating of the blank several times before they completely fill the die impression. However, prolonged hammering over a range of temperatures may result in laps or folds in the metal. Moreover if the radius is adjacent to the flash line – or metal-escape route – flash-line cracking may be encountered.

Ring-type forgings are a good example of the use of pre-formed blanks. The metal to be forged is flattened to a circular disk and a hole is bored through the center. The disk is then placed on a mandrel and forged down to the required diameter. The effect is to produce a grain flow which extends completely around the circumference. The ring is then forged on the finishing dies to the desired surface contour.

(Continued on p. A-96)

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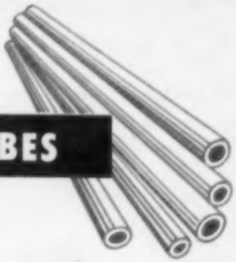

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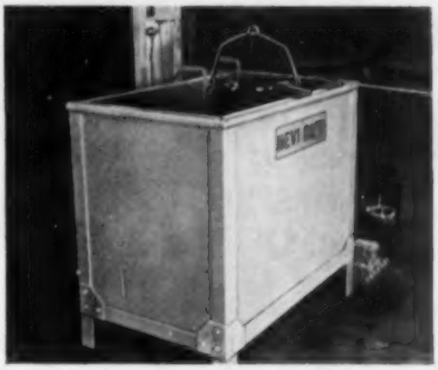

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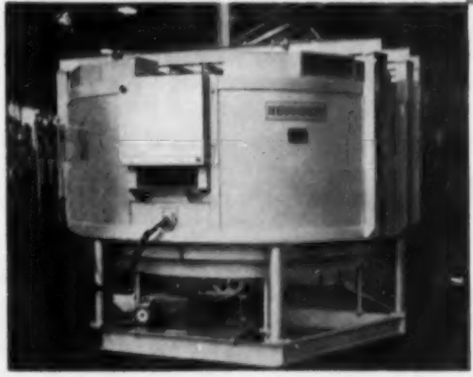

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Designed to operate at temperatures up to 2500° F. Many of these furnaces are heating jet engine parts prior to forging. A protective atmosphere prevents scale and the decarburization of high temperature alloys. Maximum capacity is 1500 pounds per hour. Bulletin 153.

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As to choice of forging stock, extruded bar, if free from defects such as "double skin" or those resulting from overheating during extrusion, is most suitable as a general-purpose material. Difficulties may arise from large grain on the end sections of extrusions unless the bars are produced by the lubricated extrusion method. The latter requires machine turning before forging.

Rolled bar is better than extruded sections for forgings which must be entirely free from coarse grain. Cast stock or material pressed from a cast ingot is useful for making forgings larger than what can be made conveniently from extruded bar. However, extrusions now can be obtained up to about 13 in. diameter and this is sufficient for most types of impact forgings. Larger pieces are best made in hydraulic presses.

Heat Treatment

Solution and precipitation heat treatments are usually carried out in batch-type electrically heated pit furnaces, in conjunction with electrically heated water quench tank and high-speed hoist. Sealing and ducting of the top of quench tanks is advisable to contain the large volumes of steam, particularly where loads of 25,000 to 30,000 lb. are being quenched.

Salt baths for precipitation heat treatment are lower in initial cost but may have higher operating cost due to excessive salt drag-out. Salt fluidity naturally is lower than with high-temperature salt baths. Another disadvantage is that they cannot be operated below approximately 300° F. and some aluminum alloys are aged at lower temperatures.

Forgings may distort on quenching and this must be corrected as quickly as possible, either in a press or by impact. With irregular shapes, it may be necessary to hold the part securely in a jig which indicates when distortion has been eliminated.

Inspection Techniques

Inspection centers around the search for cracks and folds in finished forgings, the most vulnerable spots being flash areas, radii between web

(Continued on p. A-98)

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SPRING STEEL THAT
"Fits like a glove"...
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COLD ROLLED SPRING STEELS
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Sandvik's catalog gives thickness width, hardness, types of edges and weight in pounds per hundred feet. Also includes useful reference tables ... Weights of Strip Steel, Comparative Table of Wire Gauges, Numerical Conversion Tables, Hardness Conversion Tables and a Temperature Conversion Table.

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Inspection . . . .

and ribs, and sharp bends. If defects do not extend far below the surface, they can be removed by filing at right angles to the crack; if deeper, flexible-shaft rotary cutters will do the job. If the forging becomes undersize after removal of a defect, it must be reheated, restruck in dies and again heat treated.

Crack detection is aided by anodic oxidation of the forgings, using the chromic acid process. This treatment is general practice on all finished aircraft forgings. It is a searching test for cracks since the electrolyte easily penetrates them and subsequently seeps out, leaving brown stains in the surface oxide film. The process has the advantage over etching methods of crack detection in that it may be applied to fully machined forgings without any reduction in dimensions, and also furnishes a corrosion resistant coating.

Internal cracks, for the most part, can be discovered only by ultrasonic testing, although this type of test is confined to forgings of relatively simple shape. It has not become a standard method in British industry. Most internal defects spring from unsound forging stock, so they can best be avoided by adequate testing and inspection of the material before forging.

Mechanical properties and metallurgical structures of aircraft drop forgings are checked meticulously. Each batch of heat treated forgings is represented by at least one set of three control test bars of the same analysis. Bars are forged to about 1¼ in. square at the same time as are their corresponding forgings. If the bar stock is small, control samples are heat treated without forging. They serve merely to establish the response to heat treatment of the material and not the mechanical properties of the finished forgings. The latter are checked with test pieces cut from various locations in the heat treated forgings, as specified in the design. Such tests are made on one piece from the first lot made on new dies and on further samples taken at regular intervals.

Tensile properties vary considerably according to the angle between

(Continued on p. A-100)

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For over three quarters of a century, industry's nonferrous metal users have said . . .

"SPECIFY SEYMOUR. YOU KNOW IT'S GOOD!"

NICKEL SILVER ALLOYS

Alloy Number	10A7–10%	12A1–12%	12A4–12%	15A1–15%	18A1–18%	18A4–18%
Type	Forming	Forming	Spring	Forming	Forming	Spring
Copper	71.5%	65%	56.5%	65%	65%	55%
Nickel	10.0%	12%	12.0%	15%	18%	18%
Zinc	18.5%	23%	31.5%	20%	17%	27%
Melting Point (Liq.) °F	1950	1900	1870	1970	2030	1930
Density, Lbs./cu. in.	0.314	0.314	0.312	0.314	0.316	0.314
Aver. Linear Coefficient of Expansion per °F	0.0000090	0.0000090	0.0000091	0.0000090	0.0000090	0.0000093
Electrical Conductivity IACS	9%	8%	7.5%	7%	6%	5.5%
Modulus of Elasticity (Tension) Thousands p.s.i.	17,500,	18,000,	18,000,	18,000,	18,000,	18,000,

PHOSPHOR BRONZE ALLOYS

Alloy Number	971–3%	950–5% (A)	928–8% (C)	910–10% (D)
Copper	97%	95%	92%	90%
Tin	3%	5%	8%	10%
Melting Point (Liq.) °F	1950	1920	1880	1830
Density, Lbs./cu. in.	0.321	0.320	0.318	0.317
Aver. Linear Coefficient of Expansion per °F	0.0000099	0.0000099	0.0000101	0.0000102
Electrical Conductivity IACS	22%	16%	13%	11%
Modulus of Elasticity (Tension) Thousands p.s.i.	15,000,	15,000,	15,000,	15,000,

BRASS ALLOYS

Alloy Number	265	270	280	285	287	290
Type	Yellow	Cart, 70%	Low, 80%	Red, 85%	Jwlry, 87.5	Com. Br. 90
Copper	65%	70%	80%	85%	87.5%	90%
Zinc	35%	30%	20%	15%	12.5%	10%
Melting Point (Liq.) °F	1710	1750	1830	1880	1895	1910
Density, Lbs./cu. in.	0.306	0.308	0.313	0.316	0.317	0.318
Aver. Linear Coefficient of Expansion per °F	0.0000113	0.0000111	0.0000106	0.0000104	0.0000103	0.0000102
Electrical Conductivity IACS	27%	28%	32%	37%	40%	44%
Modulus of Elasticity (Tension) Thousands p.s.i.	15,000,	16,000,	16,000,	17,000,	17,000,	17,000,

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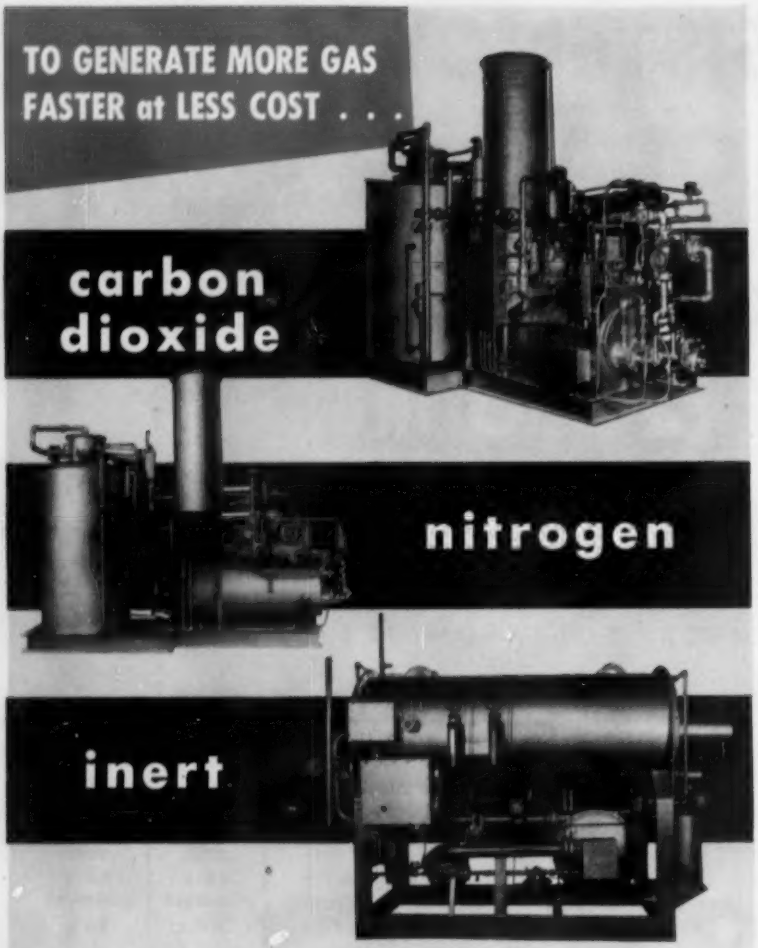

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Magnesium Forgings . . .

the axis of the test piece and the grain or fiber of the forging, being highest, of course, at the zero angle, or parallel, location.

Both macro and micro-examination are important phases of quality control in aircraft drop forgings. The former is carried out on a routine basis for checking structure, the grain flow of which is usually specified. Microsections are taken regularly from heat treated forgings to guard against overheating. Microexamination also is used to investigate defects, both in forgings and in raw stock.

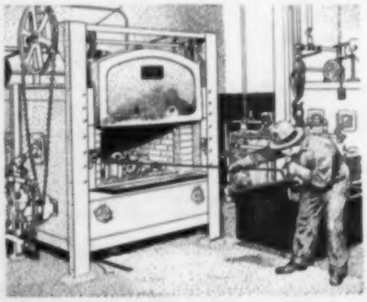
Forging Magnesium Alloy

A magnesium alloy with 3% Zn and 0.7% Zr has been found suited to high-strength drop forgings. Techniques are similar to aluminum alloys, forging temperature range being 570-930° F.

The preferred orientation which occurs on plastic deformation of magnesium gives rise to directional properties. In free forging, for example, cast stock draws out or elongates easily until the original cross-sectional area has been reduced by about one half. Further working does not produce any more elongation but results in bulging of the material from the sides. Turning the bar through 90° has the same effect and continued hammering leads to cracking along corners.

Extruded bar cannot be worked by free forging because of high directional stresses arising in extrusion. Forging such material leads to shear cracking. Cast stock, therefore, is generally the choice for both free forging and closed-die drop forging of the so-called ZW 3 magnesium alloy.

A. H. Allen



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TYPE	APPLICATION
GROUP I	**Martensitic—Straight chromium, hardenable. Machinable. Weldable. Magnetic.**
403	High stress rotating parts—1100° F. maximum. Turbine blades.
410	Valve trim, oil refinery equipment, pump shafts, heat-treated machined parts.
416	Pinions, gears, shafts, aircraft fittings.
420	Gears, shafts, molds for plastic and rubber. Valve parts.
440 A B C F	Valve parts, any place maximum hardness is required.
GROUP II	**Ferritic—Straight chromium, non-hardenable. Machinable. Magnetic. Corrosion-resistance superior to Group I.**
430	Trim work exposed to atmosphere or water. Hardware.
442-3-6	Used for scale-resisting purposes. Furnace parts, baffles, blowers, and trays.
GROUP III	**Austentic—chromium-nickel—non-hardenable.**
302	Heat treating fixtures, tank parts, mild corrosion applications.
303	Valves, valve parts, food machinery equipment, pump cylinder, free machining.
304	Dairy equipment parts, fittings, magnetic traps.
305	Textile equipment, dye vats.
309	Furnace parts, pump parts, chemical equipment.
310	Furnace conveyors, boiler baffles, oven equipment, furnace castings.
316	Valves, fittings, condensers, chemical equipment.
317	Valves, chemical equipment, pumps.
321	Stabilized—used where welding is required and welded part cannot be heat treated.
330	Furnace parts.
347	Valves, pressure fittings — stabilized — can be welded without subsequent heat treatment.

"WAUKESHA" METAL

(copper base, high nickel content alloy)

TYPE	APPLICATION
0	For high hardness—high tensile characteristics and good wearing qualities.
1	Good bearing and wear resisting qualities. Recommended for frictional parts such as scraper blades.
3	Rather hard, high tensile strength, good wear qualities. Recommended for conveyor chain links, cams.
4	Has good resistance to wear and also on high pressures. Recommended for bottle slides, pump rotors.
7	A general-purpose alloy of medium hardness. Used in many applications such as milk and carbonated beverages, chain links and sanitary fittings.
8	Recommended for use in ice cream freezer castings. Can be used as a frictional part with other "Waukesha" metal alloys.
11	This alloy recommended where tin, lead and zinc are not required. High strength.
18	Recommended for use in shafts and applications involving pressure and high tensile strength.
118	A widely used, practical alloy for valves, fittings and general applications.
21	For physical and chemical characteristics—special applications.
23	Bearing alloy to be used in conjunction to the stainless steel alloys for non-galling applications. Copper free.
88	Same as above. Recommended for more severe corrosion applications.

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INCONEL . . . Inconel is a high nickel content alloy containing chromium and iron for corrosion-resistant properties.

BRASS AND BRONZE . . . All grades of these alloys are available.

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EVERDUR . . . This is a silicon bronze alloy which in certain applications offers excellent corrosion resistance. The alloy offers the corrosion resistance properties of copper and the physical properties of mild steel.

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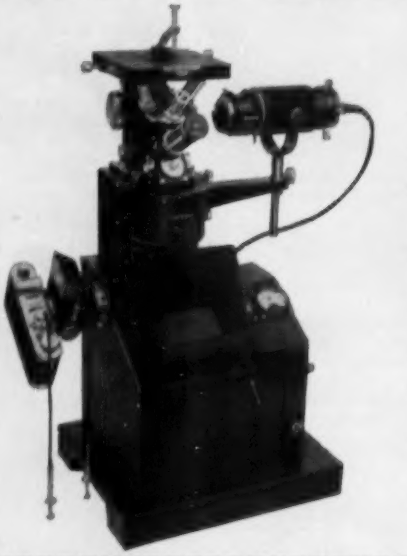

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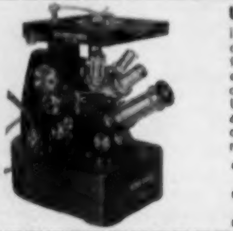

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Fatigue Strength of Aluminum Alloys*

FATIGUE tests were made by the alternating torsion method (described in *Journal* of the Institute of Metals, Vol. 72, 1946, p. 97) by which one end of the specimen (the stressed part is 0.39 in. diameter) is twisted back and forth by an electromagnetic arrangement at a frequency of about 1000 cycles per sec. The vibration of the other end is detected electromagnetically through an electronic amplifier, and the ratio of the excitation current to the detector voltage provides an indication of the internal damping. The damping capacity is measured continuously during the fatigue test to detect changes in the hysteresis loss. The surface stress is computed from the strain measured optically.

The fatigue tests were made on specimens machined from heat treated extruded 1.25-in. round bars of an alloy containing 4.4% Cu, 0.6% Mg, 0.7% Si, and 0.6% Mn.

At the highest stress used, 20,360 psi., the damping rose from the start of the fatigue test to 87×10^{-5} at 0.1 million cycles and about 185×10^{-5} at 1.5 million. At lower stresses, such as 13,730 to 17,960 psi., the damping remained practically constant at about 15 to 30×10^{-5} for over a million cycles at the higher stress, and for nearly a hundred million at the lower stress before rising sharply. This rather abrupt increase in damping could not be attributed to cracking, as two of the specimens in which it occurred were not cracked at the end of the test.

The variation of damping with strain is thus characteristic of the condition of an alloy. The change in condition due to alternating strain was compared with changes due to heat treatment. First the change in damping of a fully heat treated (precipitation hardened) specimen is moderate with increasing stress up to about 14,000 psi., but increases about 5-fold with increasing stress between about 7000 and 14,000

(Continued on p. A-104)

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*Digest of "Fatigue Phenomena in High-Strength Aluminum Alloys", by R. F. Hanstock, *Journal* of the Institute of Metals, Vol. 83, September 1954, p. 11-15.

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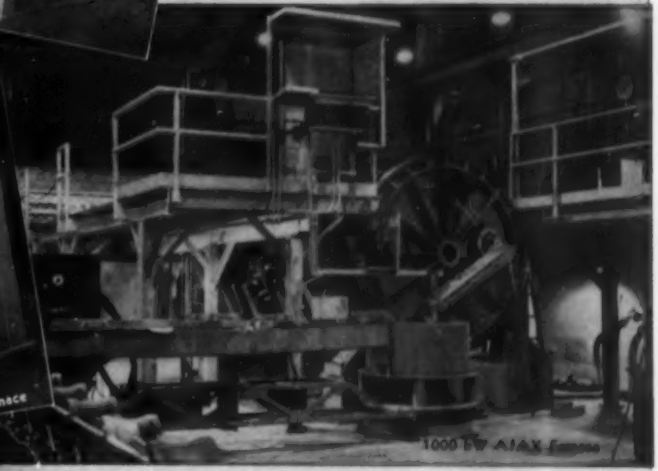

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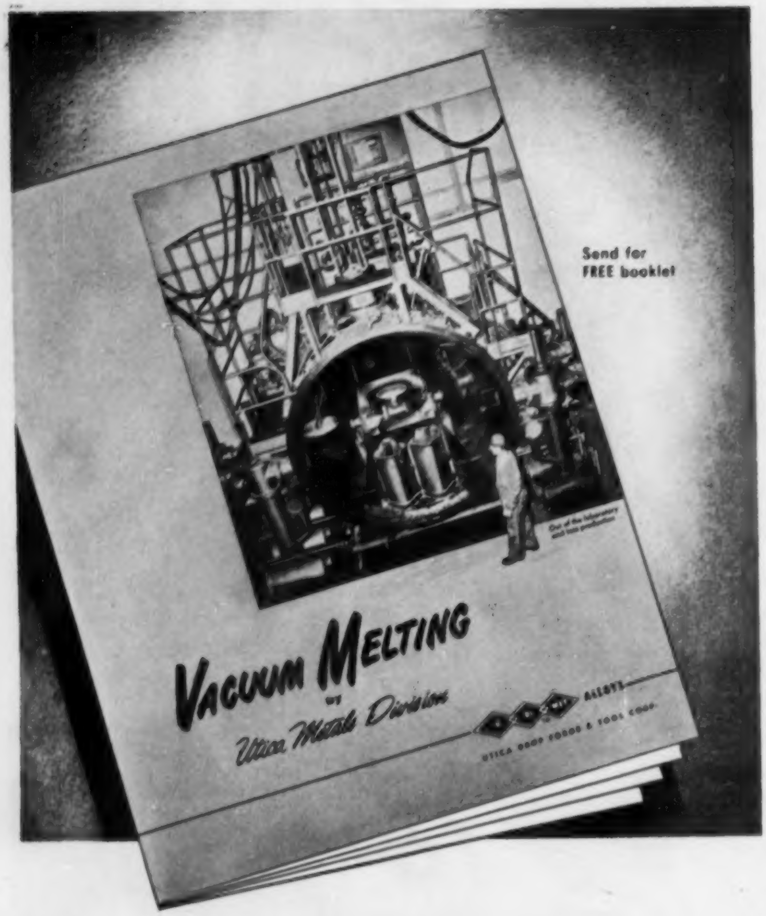

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Fatigue . . . .

psi. when the test was made after 10 million cycles of alternating torsion at a surface shear stress of 17,960 psi. Heat treating this specimen for 2 hr. at various temperatures between 390 and 570° F. caused the damping to increase faster with increasing stress, and no sign of inversion to the original unvibrated condition was shown, even though some temperatures were high enough to coarsen the precipitate. Heating to 890 or 930° F. followed by quenching and aging restored the damping-stress curve to its original flat shape, and further vibration then had the same effect as before.

Alternating strains within the fatigue range produced an effect on the damping-stress curve in the solid-solution state similar to that of thermal aging. The similarity in damping occurred only up to the stress (or strain) reached during the application of the alternating strains, higher stress giving sharply increased damping. The precipitation hardening induced by cyclic straining is therefore probably not uniform, but only in certain grains. New regions may be affected by the application of higher alternating strains for a brief period, returning the damping-stress curve to one characteristic of a thermally aged specimen.

Metallographic evidence of precipitation induced by cyclic straining was obtained from torsion-fatigue test specimens machined from heat treated extruded 1.25-in. round bars of an aluminum alloy containing 0.4% Cu, 2.7% Mg, 0.5% Mn, and 5.3% Zn. Short, fine circumferential cracks grouped in lengthwise streaks on the surfaces of tested specimens are illustrated. These first appeared with the rise in damping preceding the development of a major fatigue crack. Precipitation associated with these streaks of incipient cracks is also illustrated. Solution heat treatment at that stage removed the precipitation, but not the cracks. The precipitation is believed to have occurred before the cracks.

The damping of a specimen rose from 15.1×10^{-5} to 436×10^{-5} on vibration at a stress of 20,360 psi. for 0.38 million cycles, and some

(Continued on p. A-106)

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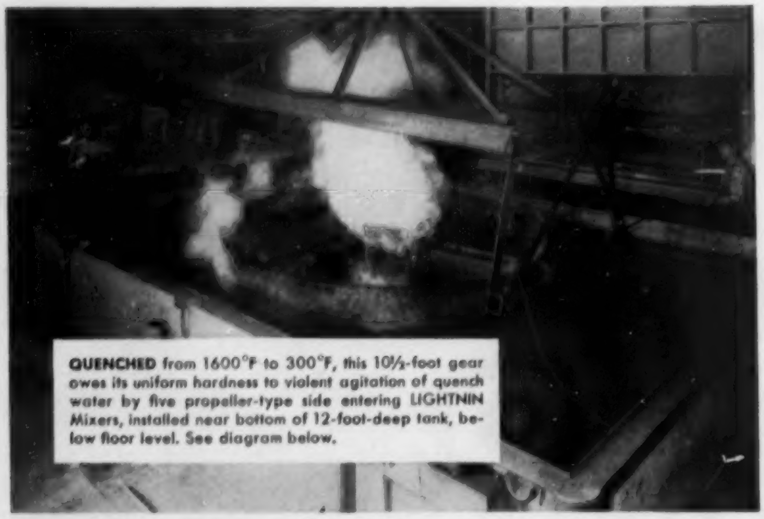

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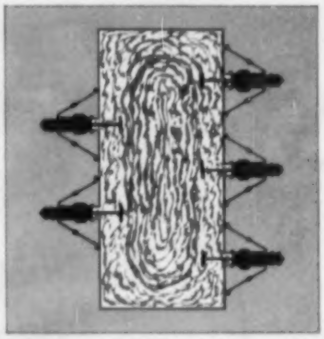

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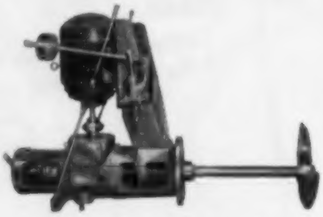

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Fatigue . . . .

fine surface cracks were found. After heat treatment to remove precipitation the damping fell to 10×10^{-6} and when vibrated again at 20,360 psi. for 0.14 million cycles the damping rose to 200×10^{-6} and a major fatigue crack formed. Since the damping fell on heat treatment even though fine cracks were present, the rise in damping which precedes fatigue failure must be caused primarily by precipitation induced by cyclic straining, rather than by the cracks.

Aluminum alloys having high static strength as a result of precipitation are unstable in fatigue. Cyclic stressing affects them like aging at too high a temperature, except that the precipitation is localized rather than general, and the static strength may thus not be affected. Their fatigue strength is determined by the magnitude of the cyclic stress necessary to initiate precipitation and by the strength of the regions where the over-aging occurred.

G. F. COMSTOCK

Method for Removing Oxygen From Titanium*

A. B. OSBORN of the Royal Aircraft Establishment, succeeded in removing at least 70 to 80% of the oxygen from oxygen-titanium alloys by vacuum sublimation. However, the amount of electrical energy was prohibitive for a competitive commercial process.

Titanium-oxygen alloys were prepared with the intended compositions of 2, 6, and 16% (by weight) oxygen – using titanium sponge having a Vickers hardness of 176, and titanium dioxide powder – to give alloys containing alpha plus beta, alpha, and alpha plus TiO, respectively, at 2730° F. The 2% oxygen alloy was triple arc melted in an argon atmosphere and hot forged into

(Continued on p. A-108)

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*Digest of "An Attempt to Separate Titanium from Oxygen by Vacuum Sublimation, and Some Measurements of Evaporation Rates", by A. B. Osborn, *Journal* of the Institute of Metals, Vol. 83, January 1955, p. 185-188.

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bar 1 cm. diameter and 12 cm. long. Because of brittleness, the 6 and 16% oxygen alloys were crushed to powder after arc melting and pressed and sintered in vacuum, then machined to the same size bar as the 2% alloy. X-ray examination of the two high-oxygen alloys suggested values of 6 ± 1 and 16 ± 2% oxygen by weight.

The apparatus consisted of a water-cooled Pyrex cylinder with the titanium-oxygen alloy bar suspended vertically inside and the appropriate vacuum seals and connections to supply the heating current to the specimen and allow for its thermal expansion. The specimen was surrounded by a cylinder of titanium foil, which remained cool enough to condense and collect the sublimate.

Each bar was heated to 2730° F., as measured by an optical pyrometer, by passing alternating current through the specimen. A temperature of about 2910° F. was required to evaporate the 16% alloy. A pressure of less than 4×10^{-4} mm. Hg was maintained during the evaporation. After an adequate coating (about 2 g.) had deposited on the titanium collector, the foil was removed, cut into strips, and arc melted into a button. Hardness measurements were made on the cross section of the button and the oxygen content estimated from the hardness curve derived by Jenkins and Worner. The results are in the tabulation on p. A-109.

Each sublimate contained about 70 to 80% less oxygen than the titanium alloy bar from which it was evaporated. Since the collector foil was known to contain some oxygen originally, actually more oxygen was removed than is indicated in the table.

The evaporation rate of the titanium-oxygen bars was calculated from the weight of sublimate collected on a separate slip of titanium foil mounted just outside a 5-mm. diameter hole in the larger foil collector, with the area through which the vapor passes and the time being known. The necessary corrections

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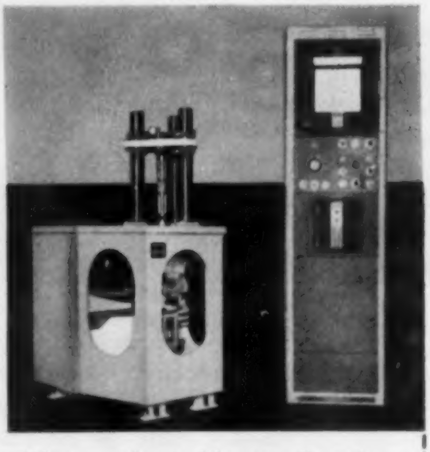

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were made for the absorption by the water bath and the various glass surfaces, through which the optical pyrometer temperature measurements were made.

The evaporation rates determined for the 6% oxygen alloy, which is alpha plus beta at 2730° F., are of the same order as those for pure titanium. However, the value found for the 16% alloy, which is alpha plus TiO at 2900° F., is about one-seventh of that for pure titanium.

If composition followed the same temperature law as titanium, the volatility at 1940° F. would be negligible (about 0.4×10^{-10} g. per sq.cm. per hr.). The author therefore repeated Ehrlich's experiment in which he heated the 6% alloy in vacuum in both alumina and zirconia crucibles for 36 hr. at 1940° F. and found no change in weight. This result confirms the prediction that the alloy with 6% oxygen is not volatile at 1940° F.

The rate of evaporation measurements made on the 6% alloy showed that the purification of 1 lb. of titanium in the experimental apparatus would require about 1600 kw-hr. of electrical energy. The author predicts that the efficiency of the process might be reduced to 800 kw-hr. per lb. of material, but this is still too high for an economic industrial method of purification.

R. J. McClintick

Oxygen Content and Hardness

Titanium Alloy Bar	Weight of Sublimate	Weight of Foil	Vickers Hardness*	Oxygen Limit†
2% Oxygen	3.6 g.	1.7 g.	272	0.6%
6% Oxygen	2.0	1.7	315	1.0
16% Oxygen	1.6	1.8	569	5.1

*Button of foil plus sublimate; hardness of the titanium collector foil was 284. †Estimated upper limit in sublimate.

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Effect of Iron on Aluminum Casting Alloys*

This paper describes how the deleterious influence of iron on type A-S 13 Alpax alloys can be decreased. The composition is Si 12.0 to 13.7%, Fe 0.75% max., Mn 0.30%, other elements not over 0.10%.

Microscopic examination reveals four phases in these alloys: *(a)* crystals of alpha solid solution of aluminum containing small quantities of iron, silicon, and manganese; *(b)* silicon lamellae that accompany the alpha phase in eutectic regions, silicon being present as regular crystals in improperly modified alloys; *(c)* plates of intermetallic compound, *m*, present in alloys that are high in iron and low in manganese; *(d)* massive crystals of intermetallic compound, *c*, in alloys that are high in manganese and low in iron.

The unusual constituents of these alloys are coarse silicon crystals and phases *c* and *m*. They are hard and may act as hard spots during machining. Phase *m* is undesirable for two additional reasons *(a)* it forms large, brittle plates that make the high-iron alloy very brittle, and *(b)* interfere with the feeding of the casting.

These three constituents are important only when they are primary phases, because, when they form before the alpha phase, they are coarse. The quality of high-iron A-S 13 alloy can be improved by avoiding the formation of crystals of *m*, by decreasing their size, or by replacing them by the less detrimental *c* phase.

The author has tried to determine the primary zones in the Al-Fe-Si-Mn diagram for the usual cooling conditions and to establish a relationship between chemical composition and mechanical properties.

The alloys investigated contained between 12.4 and 13% silicon, between 0.55 and 1.20% iron, and between 0 and 1.30% manganese. Test bars were cast in sand and in permanent molds. *(Cont. on p. A-112)*

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*Digest of "Influence of Iron and Manganese on Type A-S 13 Alloys", by Claude Mascré, *Fonderie*, Vol. 108, January 1955, p. 4330 to 4336.

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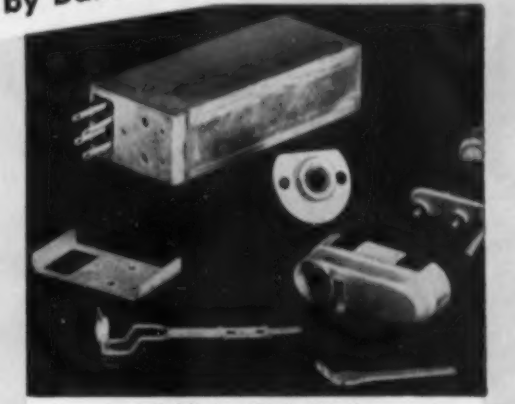

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Fe in Al Alloys . . . .

The author presents two diagrams showing the theoretical and experimental regions of primary solidification. The first diagram shows that in modified alloys, phases *c* and *m* are primary at lower iron and manganese contents than in unmodified alloys. The other diagram indicates that, as cooling is accelerated, the primary alpha region is increased; in other words, the higher the cooling rate the higher the manganese and iron contents can be without phases *c* and *m* being primary.

The ultimate strength and elongation of test bars cast in sand and in permanent molds drop rapidly with the appearance of primary *m* phase. The primary *c* phase is less detrimental to the ultimate tensile strength but causes the elongation to drop rapidly.

For given iron content and cooling conditions the amount of manganese to be added to obtain maximum mechanical properties was determined. No manganese addition is needed in sand castings if iron is lower than 0.75%, in permanent mold castings if iron is lower than 0.90%, and in very thin permanent mold castings if iron is lower than 1.05%. In sand castings containing more than 0.75% iron, the manganese addition required will be given by $\%Mn = 1.7 \times (\%Fe - 0.5)$; in permanent mold castings containing more than 0.90% iron the amount needed is $\%Mn = 2.2 \times (\%Fe - 0.5)$.

Two types of segregation were noticed in these alloys: *(a)* microsegregation resulting from the solidification process, and *(b)* gravity segregation of silicon crystals and of phases *c* and *m*. The latter type is the more important. If solidification is too slow, primary silicon crystals will float and primary crystals of phases *c* and *m* will sink.

The conclusions of this study are that it is preferable to keep the iron content below 0.75%. If it is higher, its deleterious effects on mechanical properties, machinability and soundness are decreased by increasing the solidification rate or by using a moderate modification treatment. If these fail to give satisfactory results, manganese may be added.

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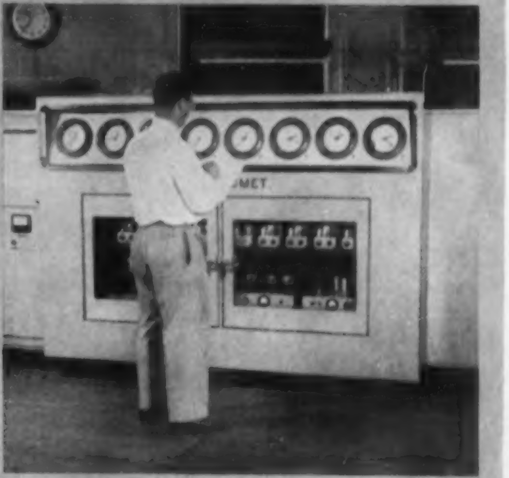

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Monolithic Rammed Linings for Aluminum Melting Furnaces*

ADVERSE economic factors of induction melting are offset by the reduction in melt-loss through oxidation and volatilization, especially with charges of light-gage scrap. Improved alloying and homogeneity of the melt develop from the stirring action produced by electrodynamic forces within the molten metal. Since the heat is generated within the body of the metal, the temperature of the refractories, even in furnace melting channels, does not greatly exceed the final operating temperature of the melt.

Induction melting of aluminum alloys has been retarded by problems of devising a refractory lining with adequate metallurgical, thermal and mechanical properties to give economic durability. The twin-bath, horizontal channel type of low-frequency induction furnace is most critical in this respect because its shape is intricate and the entire lining, comprising baths and melting channels, must be installed in one operation.

The choice of material and method of shaping for induction furnace linings handling aluminum alloys depends upon four factors:

1. Durability under conditions of thermal stress and shock.
2. Mechanical wear from charging and maintenance, and erosion from flow of molten metal.
3. Ease of manipulation of material during lining installation or repair.
4. The refractory costs.

Linings should have a glazed or "fritted" surface to be as nearly non-wetting as possible. Surface and body should be impermeable to the melt and subsurface material should remain unburned to retain maximum strength and resilience under thermal and mechanical stresses.

Early attempts to cast refractory cement linings for the twin-bath induction furnace as monolithic envelopes behind refractory brick walls ran into difficulties from cavities and spongy areas. Furthermore, the large surface area exposed during casting was likely to lose too much moisture and bond poorly between layers if, during installation, operations were temporarily discontinued. Prefired refractory blocks, tongued and grooved for assembly and laid with refractory cement were considered as linings. Lack of uniformity in the joints and the varying effect of drying-out temperature on the cement and blocks caused lining cracks in surface joints. Finally fully monolithic rammed linings, fired in place after being shaped, were investigated.

Three ramming methods have been tried, designated as flat, "light-stitch" and "heavy-stitch" ramming, the latter two adapted from the original German practice. Refractory mix for all three is acid, approximately

---

*Digest of "The Choice and Construction of Monolithic Linings for Twin-Bath Induction Furnaces for Melting Aluminum Alloys", by E. J. Thackwell, *Journal of the Institute of Metals*, Vol. 83, February 1955, p. 283-294.

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72% silica clay and 28% quartz. For the flat-rammed lining, however, about 10% additional silica was used with 4% sodium silicate in a finer mixture. Moisture content is held between 5.2 and 6.5%.

Flat ramming was done with pneumatic hammers, delivering 1400 blows per min., at 80 to 90 psi. compacting tools had flat working faces with contact surface of 3 × 1⅛ in. This lining was installed in a single-bath vertical channel furnace and required 7000 lb. of refractory. Material was spread in layers of about 2⅝ in. loose depth, then compacted to 1⅛ in. After each layer was completed, the surface was chipped crosswise with hand tools and loose material removed to form a lock bond and knit together each successive layer. Forms backing up the lining were of mild steel lightly oiled to prevent adhesion. A complete lining was produced in 10 hr. It had a service life of 4 to 6 weeks, gradually deteriorating to a laminated structure with slag and oxide penetration at the interlamination bands. Nonwetting characteristics were poor.

In light-stitch ramming, refractory was spread in layers 1⅛ to 2 in. thick, and on top of each was left a ¼-in. layer of loose material which was crisscross scratched with hand tools to provide a bond for successive layers. The idea was to "stitch" the material together, so to speak, without formation of well-defined layers, and also to avoid over-ramming. Total weight of refractory in a twin-bath furnace was 7 tons, and the lining was completed in 40 hr. It lasted 9 months. There was slag pickup and oxide penetration which made cleaning of furnace channels extremely difficult.

To provide a denser lining, heavy-stitch ramming was introduced, with a somewhat different design of compacting tool, having a contact face 1 3/16-in. long with a 1/16-in. radius running into a 45° taper at the sides and ends. Refractory was added in 1-in. layers; the effect of the hammer tools was to knit successive layers together into a homogeneous mass. Each layer was finished with rapid hammer runs for a closely serrated finish. There was no scratching or chipping.

A lining of this type has now been in service for 32 months melting principally light-gage scrap much of which is lacquer-coated. The surface shows good nonwetting qualities, absence of visible layers and negligible oxide penetration. Although it represents a departure from non-dense resilient linings, its hardness and good durability more than compensate for the additional radiation from the denser structure.

Linings are dried out in two stages, first air drying at shop temperature for a minimum of eight days, then raising the temperature gradually to that of the molten metal to be introduced, requiring at least another eight days. They are heated by coiled electric elements mounted on ceramic insulators about 7 in. from the lining.

In general, the purpose of the installation and drying out of these monolithic linings is to hold mechanical stresses and thermal shock to a minimum. Even after introduction of molten metal and for the first two weeks of operation, care is taken in charging and cleaning the bath walls to avoid damage to refractory surfaces which may not be completely fritted or hardened.

A. H. Allen

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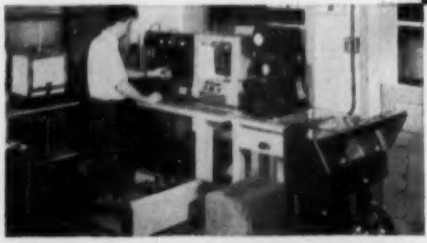

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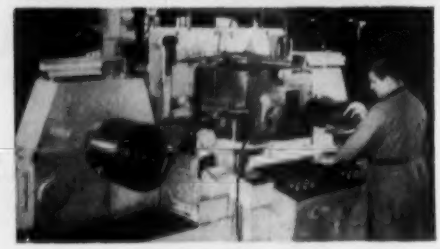

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Fatigue Failures in Aircraft*

In 1950, the U. S. Navy Bureau of Aeronautics became seriously concerned about several in-flight accidents of attack-type airplanes which could not be satisfactorily attributed to the usual causes. It was determined that during dive-bombing and rocket-launching maneuvers, squadrons operating these airplanes were frequently exceeding flight restriction limits. Some of the airplanes had exceeded design limit load conditions as much as 20 times. Accordingly, a project was initiated at the Aeronautical Structures Laboratory, Naval Air Material Center, to determine the effect of accelerations in excess of design limit load on the service life of the structure. The load range was also extended to include values below limit load so as to permit the accumulation of sufficient data to obtain an S-N curve for the outer wing panel.

Prior to completion of the repeated-load tests, a crash of a piston-engine fighter airplane and subsequent inspection of several similar airplanes awaiting overhaul indicated that fatigue might be a possible explanation for this crash. These ships were being used for intensive training in ground-support tactics, and it was standard practice to perform 12 or more rocket launching runs with pull-out accelerations near design limit load conditions during each hour of flight. Accordingly, a large number of high-load-level pull-outs were rapidly accumulated by the airplanes. A test program was undertaken, therefore, for the dual purpose of obtaining information concerning the capability of the wings of this type of craft to withstand repeated applications of loads representing high-acceleration pull-outs and of determining the structural change needed in the wing center section to increase the useful life. The question then arose concerning the fatigue characteristics of the wing structures of the more modern jet-type craft. The trend in recent years has been toward structures with increased mean stress levels; this trend, viewed in the light of the test results obtained under the two previous programs, indicated that fatigue might be a serious factor in the operation of jet-engine fighters. Tests were performed to determine an S-N curve for this structure and to obtain information concerning Miner's cumulative damage ratio.

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*Digest of "Investigations Concerning the Fatigue of Aircraft Structures", by R. A. Carl and T. J. Wegeng, Preprint No. 68, American Society for Testing Materials, 1954, 23 p.

All test specimens were complete aircraft wing structures or portions of a wing, such as the outer wing panel, that were believed susceptible to fatigue failure. Specimens were mounted in a manner that duplicated the root-end restraint of the structure as mounted on the airplane. Beam bending loads were applied to the test specimen through a tension-patch, whiffletree, and hydraulic-jack loading system, and chordwise loads were applied through felt-lined straps cemented to the panel at appropriate spanwise intervals. For static tests, the loads were applied to the hydraulic loading system by means of hand-operated pumps. For repeated-load tests, these pumps were replaced by motor-driven pumps, and the loads were controlled by a calibrated tension loop, equipped with upper and lower load limit microswitches which operated a solenoid-controlled, hydraulically actuated bypass valve. The load was automatically cycled between the upper and lower load limits for the test being performed. All the tests were conducted with the lower stress level held constant at a value corresponding to an acceleration of 1 g (acceleration of gravity). The upper load was varied from panel to panel. The frequency of loading varied from approximately 4 cpm. (cycles per min.) at 60% limit load to 2 cpm. at 120% limit load. Airplanes usually are designed to support 1.15 times limit load without yielding and 1.5 times limit load without failure. Thus, the stress level in a critical member of the structure at limit load is approximately 67% of the ultimate strength of the material of that member.

In the first test program, outer wing panels from a piston-engine, propeller-driven, low-wing attack

(Continued on p. A-118)

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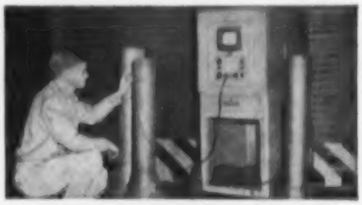

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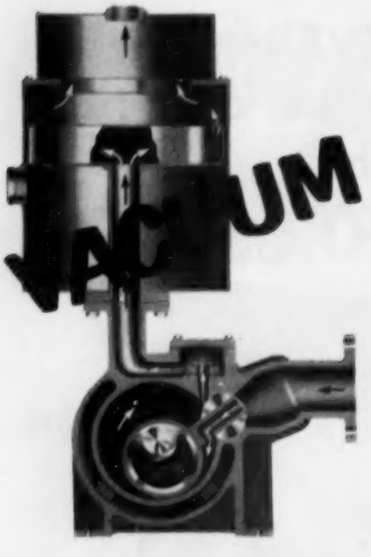

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Aircraft Failures . . .

airplane was utilized. The testing condition was representative of a positive low angle of attack pull-out in which one of the 500-lb. bombs mounted on the wing racks had been dropped, but the bomb on the opposite wing had not, thus requiring a small amount of aileron displacement to maintain symmetrical flight. A static test was first performed, failure occurring when 154% limit load was applied. The failure apparently originated in the lower wing skin immediately aft of the main beam at station 160 and was followed by a tension failure of the lower main beam capstrip at station 162. These station numbers refer to spanwise locations on the wing measured in inches from the center line of the airplane. Repeated-load tests were then performed with one panel at a time installed on a wing center section which was used as a mounting jig. A total of nine outer wing panels, including the static test panel, were tested in the program. The tests showed that the lower spar cap crack was a first indication of fatigue damage, followed by cracking of the tension skin, and then by total failure of the panel. The lower hinge fitting in the wing center section was also subject to failure from fatigue.

For the second test program, four piston-engine fighter airplanes were obtained for testing. Cracks in the spar web near the wing-fuselage juncture strongly suggested the possibility of fatigue as a cause for failures in the wing structure of this type of airplane, particularly in view of the repeated-load test data being accumulated at that time on the attack airplane. All craft had been in service for a considerable time. As a consequence, the portion of the life of the structure which had been "used up" during service could only be estimated from an analysis of the log book. Two of the ships had cracks in the main spar web beneath the web doubler plates on both starboard and port sides extending upward and inboard for approximately 2 to 3 in. from the lower intersection of the wing and fuselage. The third airplane had a

(Continued on p. A-120)

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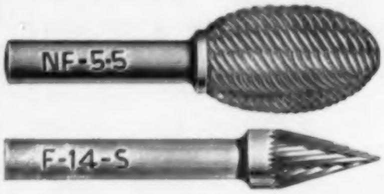

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Aircraft Failures . . .

crack in the main spar web at approximately station 15, again measured in inches from the centerline of the wing, extending approximately 9 in. up from the fuel strainer inlet hole. The fourth airplane had no visible cracks in the spar web. In addition to these defects there was rivet slippage of the skin attachment rivets along the upper and lower spar caps outboard of the fuselage on all four craft.

With the exception that loads were applied to the entire fighter wing rather than to the outer panel of one side only, the test method employed was generally similar to that used for the attack airplane. The effect of the spar web cracks on the fatigue life of the structure was observed closely during the repeated-load testing for three of the ships; two of them developed failures remote from the cracked region. The third failed in the region of the crack after the incorporation of the first modification; however, the failure did not extend along the crack. In no case was there any apparent lengthening of the cracks due to the repeated-load tests. One static failure occurred along the line of the crack, but the failing load was sufficiently high (158% limit load) to lead to the conclusion that the crack had no appreciable effect on the static strength of the wing. It would appear, therefore, that these cracks acted as stress-relievers in this instance and did not play a primary role in the fatigue life of the aircraft structure.

In the final program, a straight-wing, high-performance jet-engine fighter airplane was tested. It was thought that repeated-load tests of the outer wing panels could be made to obtain an S-N curve, and then by means of repeated-load tests of two full-strength panels, this S-N curve could be interpreted in terms of the fatigue life of the full-strength panels. The test method was similar to that used for the attack airplane. Repeated-load failures occurred in the same general areas of the spar cap as those of the static test failures; the tapped screw holes in the vertical legs of the capstrip apparently were the primary contribu-

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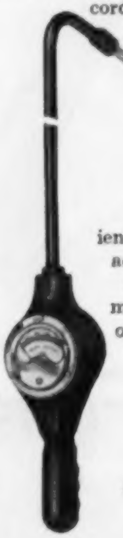

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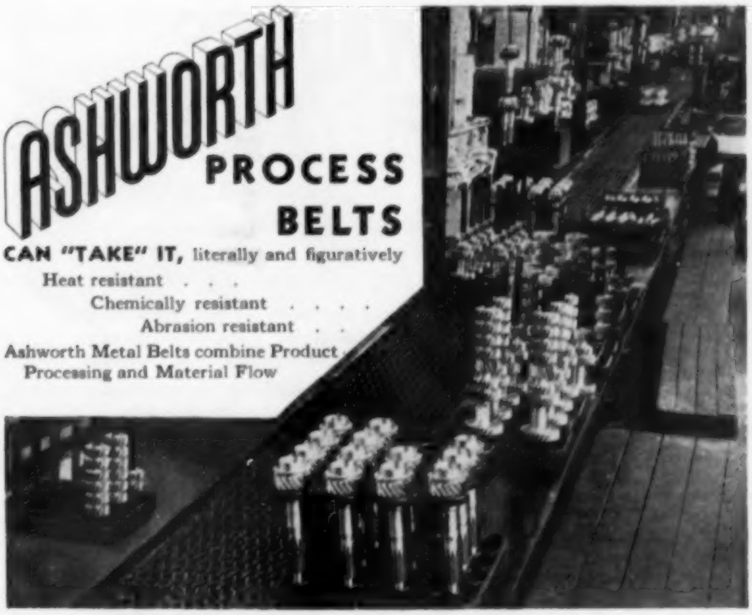
Aircraft Failures . . .

tors to failure of the panels under both static and repeated-load conditions. Initial cracking started no later than 2500 cycles and probably originated near the 1-in. bolt hole through the aft capstrip. Miner's cumulative damage ratio was also determined for spectrum loading conditions of several additional jet-fighter panels.

In plotting their data, these authors used the reciprocal of the load level for the ordinate of an S-N plot. This leads to straight lines; it is particularly interesting that the data from the attack and jet-fighter airplanes lie almost parallel. This suggests that future tests using equivalent load levels might be simplified to the extent that only check points need be obtained at two load levels to determine the location of the curve with respect to the other curves. If parallelism were not indicated, further testing would then have to be undertaken.

From their plot of stress concentration factor *Kt* vs. mean stress S_m, several further research requirements are indicated. First, there is a great need for additional notched-specimen fatigue test data for *Kt* values up to 6.0, particularly for the range between 100 and 10,000 cycles. This information should be obtained for extruded and bar-stock specimens as well as sheet specimens so as to provide the designer with information applicable to the components he must use in his designs. Second, the designer should devote increased attention to his detail design so as to reduce the composite stress concentration factor of highly stressed areas. Finally, information is needed on the number and frequency of moderate and high load levels experienced in service operations. If accurate data of this kind can be obtained, and pending further refinements in the theory of fatigue, it might be possible to phrase design criteria which will lift aircraft out of the susceptibility range for fatigue failure.

C. A. Zapffe



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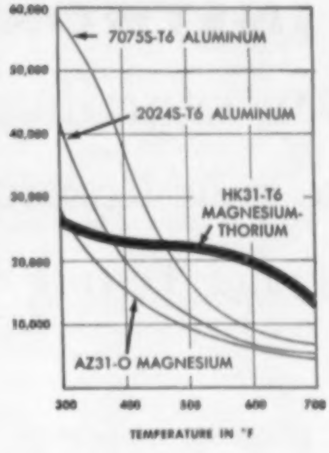

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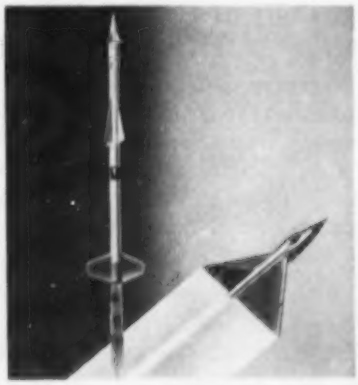

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(Continued on p. A-123)

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*Digest of "Quality Control — Use of Statistical Methods in Steel Industry", by A. V. Sukhatme, *Transactions of the Indian Institute of Metals*, Vol. 7, 1953, p. 123-136.

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Statistical Control . . .

slabs being sheared within 2 in. on the high side and quite often slightly on the lower side.

3. The Dual Control Chart – "Track time" is the time interval between teeming and charging of ingots into the soaking pits. The longer the track time, the shorter the soaking time. Two control charts, one for track time and the other for soaking time, were used. However, unavoidable delays in switching required picking the best times for soaking.

A dual control chart was used to establish "regression coefficients". Limits were set to show whether the foremen were correcting out-of-control situations by altering the soaking practice.

4. Correlation Analysis – In studies of the economics of the melting shop, three factors affected the rate of production – number of furnaces in operation, idle time and time of heat. By correlation analysis it was determined that: Production rate per shift $Y = 630.12 + 217.22 \times$ number of furnaces in operation $- 132.11 \times$ time of heat $- 166.000 \times$ idle time. By solving the equation for a number of situations, the following results were shown:

Variation due to number of furnaces in operation 11%

Variation due to the time of heat amounted to 51%

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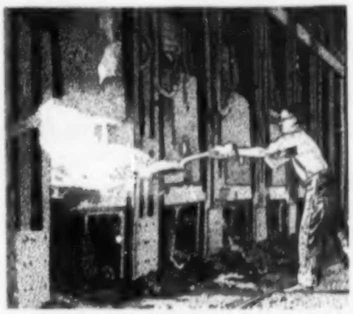
The residual variation was due to all other factors not under scrutiny and was small enough to be ignored. Obviously time of heat was the important factor in this situation.



5. Sampling – Accuracy of our 90-ton scale was not good. Therefore incoming zinc slabs were weighed in small lots. It was noticed that individual slab weights were more or less equal, therefore the average weight per slab times the number of slabs in the shipment could be used to give an accurate estimate of the total weight in the shipment. Since the statistical variation was small, a more accurate estimate of the weight of the whole shipment was possible than by weighing the entire lot on the 90-ton scale. Sampling was used to determine the average weight of slabs; considerable labor was saved.

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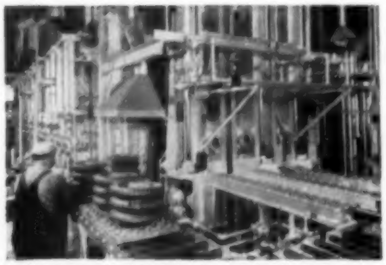

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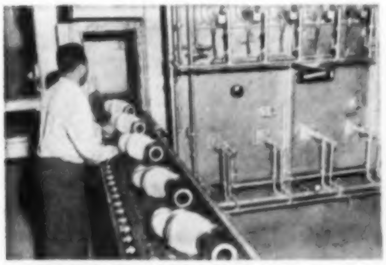

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